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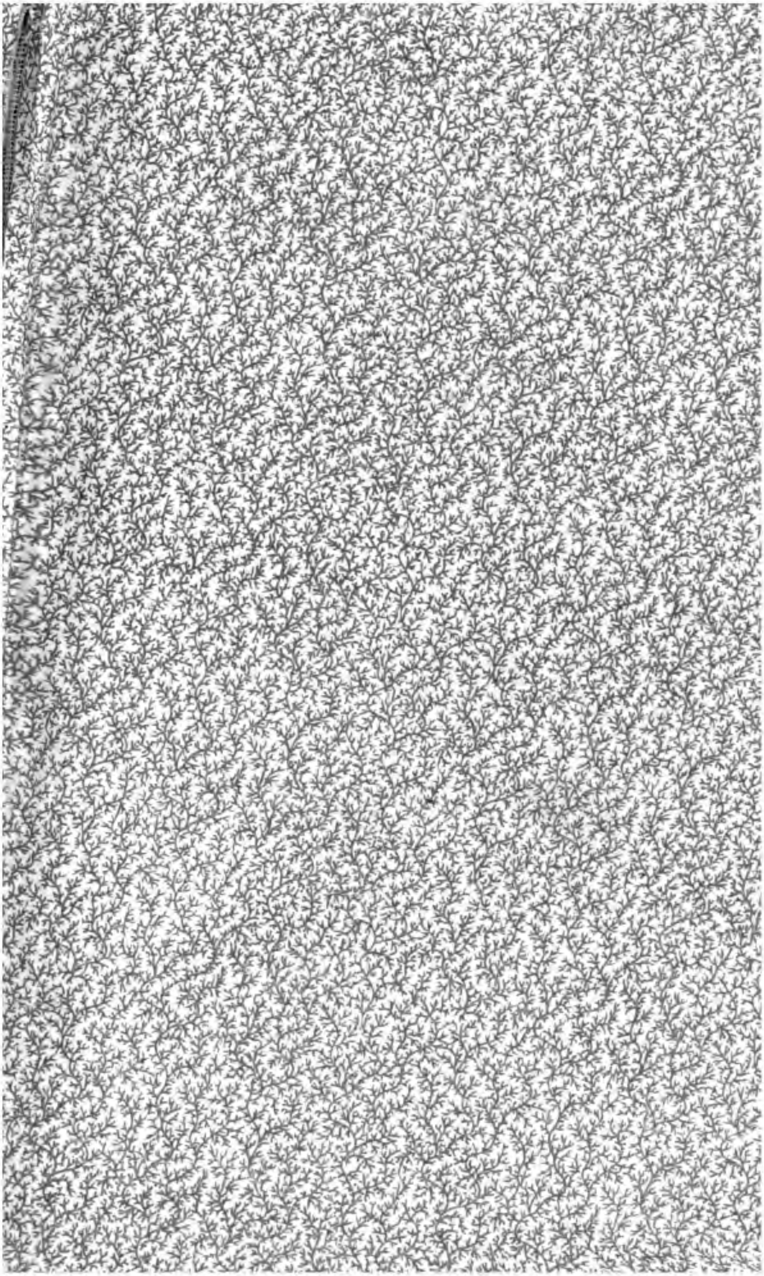

OUTLINES

OF

ELECTRICITY AND MAGNETISM

BY

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PREFACE.

It is not possible for an elementary text-book to be up to date. Before any theory is sufficiently established to find a place there, new views are already appearing, modifying our ideas.

At the same time the changes in the modern conception of electrical action demand more recognition than has been given them. Since the student must necessarily form some definite idea as to how such actions take place, it is important that these ideas should be, from the very first, in accordance with the best theories. No subsequent effort can take the place of correct initial conceptions.

This book makes no claim to be a complete treatise. While adapted to somewhat elementary courses, I hope it may also serve as a clear and logical syllabus for more advanced ones. Although much has been omitted that many would wish to include, I believe that I have included little that any would wish to omit.

C. A. P.

Knoxville, Tenn.,
Nov. 6, 1896.

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OUTLINES OF
ELECTRICITY AND MAGNETISM.

INTRODUCTION—DYNAMICS.

The Physical Sciences are concerned with the nature and effects of various forces. There are, however, certain fundamental ideas in reference to the nature and operation of force which need to be grasped before taking up the study of any special branch of Physics. I give here a brief outline of some of the main principles of dynamics, but at the same time urge the importance of studying some more extended treatment—such as the first 150 pages of Lodge's Mechanics. Do not omit to work the problems in connection with reading the text.

1. **We Learn of Nature by our Senses.**—Our knowledge of nature and her laws comes to us through our senses. When we exert a force we are conscious of the exertion, and when a force is exerted upon us we perceive it by our senses. Daily experience teaches us that, by the exertion of force, we are able to put bodies into motion, or if they are already moving, their motion may be stopped or changed by the action of force. From our observation we infer that bodies never start of themselves, and that they stop moving only because some force (usually friction) stops them.

2. **Newton's First Law.**—These facts were first summarized by Newton, who stated that bodies cannot, of them-

selves, change either the direction or rate of their motion. His original statement of this fact is called Newton's First Law of Motion.

Since all bodies are acted upon by forces, we never see anything which moves uniformly in a straight line because left to itself. The earth in its orbit moves at a nearly uniform rate, but the direction of its motion is continually changing. We know that the attraction of the sun is the force which draws it aside; and wherever we thus find motion which is not uniform or whose direction is changing, we always look for the force which produces the change.

This tendency of a body to preserve its motion unchanged is called Inertia.

3. Inertia and Mass.—All bodies do not have the same amount of inertia. Place two balls of different weight upon a marble table or sheet of glass. (They may be of the same material or not.) Touch the balls, and you will notice that the heavier one must be pushed harder than the light one to give it the same motion—not because it is heavier, for the weight of each is supported by the marble slab, but simply because the heavy ball has more inertia than the other. The heavy ball is therefore said to contain more matter than the light one.

The amount of matter in any body as measured by its inertia is called its Mass.

It must be noticed that this is a very different thing from its weight, which is simply the force of its attraction by the earth. The inertia—and mass—of a body at the centre of the earth or on the surface of the moon is the same as its inertia in New York; its weight is zero at the one place, and at the other is one sixth as great as in New York.

For some reason, as yet unknown, two bodies of the same weight have also the same mass, and a body weighing twice as much as another has also twice its mass. This makes it very convenient to compare the amounts of matter in bodies by weighing them, but at the same time leads to some confusion of the two things, which are in reality quite different.

4. Newton's Second Law of Motion.—If two balls of the same mass are put side by side on the marble slab, and one is pushed twice as hard as the other, it will start off with twice the velocity. Forces may therefore be compared (or measured) by the velocities which they produce. Newton's second law of motion is the statement of the fact that change of motion is proportional to the force producing the change, and is in the direction of the force. ("Change of motion" is the total change in its amount, including the change in velocity and the quantity of matter that has its velocity changed.)

Thus, if a body whose mass is M increases its velocity by a in one second, its "change of motion" is Ma, and Ma is proportional to the force that produces the change.

If a ball at rest is struck by a bat, the ball flies off in the direction of the force. If the ball is thrown and strikes the bat on one side, it flies off obliquely. The change in its motion is in the direction of the blow, but its actual motion is made up of its original motion and its change of motion combined.

5. Acceleration.—The rate at which velocity changes is called acceleration. Acceleration, and not motion, is the result of force. Motion is as truly the natural state of a body as is rest. When we see a body in motion we naturally ask "what set it going." When we see a thing at rest we might as naturally ask "what stopped it," except that the force of friction is commonly responsible for the state of rest. When we extend our observation to the heavenly bodies, which move with little or no friction, we find that they are all moving with very great velocity. It takes no force to keep them in motion, but would require a great force to stop them.

6. Motion and Rest are Relative Terms.—Even those things on the earth which we commonly consider to be at rest are only at rest when compared with the earth, for they, and we, are being carried rapidly round the sun by the motion of the earth, and with the sun are travelling through the unknown depths of space. It is plain, then, that rest and motion are purely relative words. When on a steamboat, those objects are "at rest" which are moving with the steamboat; when in the fields, those are "at rest" which are moving with the earth; when considered with reference to the planets and "fixed" stars what shall we take as the standard from which we may measure motion? We need only to make the attempt to see how meaningless the word "rest" has become. Still, there is little danger of ambiguity in the words "rest" and "motion," as the connection usually shows what they mean.

7. Energy and Work.—Suppose that a heavy block of stone must be raised from the ground and placed in position in a wall. A derrick with a windlass is used, and by turning the handle through a certain distance—say, five times round—the stone is raised one foot. To raise it two feet will require the handle to be moved through twice the distance. Again, to raise a block of twice the weight will require twice the force to be applied to the handle. By a different arrangement of pulleys, the stone might have been raised with one half the force, but (friction aside) the handle would have travelled through twice the distance.

The product of a force multiplied by the distance through which it moves the body upon which it acts * is called Work.

This defines a quantity which is of the greatest interest and importance in Physics, but must not be thought to be

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* This is true only when the body moves in the direction of the force; otherwise that part or "component" of the force which is in the direction of the motion must be used in place of the total force.

the same thing that is meant by "work" in ordinary language. It may be harder for a man to stand still than to walk, and going down hill may be more work than going up, but in neither case does the man, in this technical sense, do any work. Ordinarily the two senses agree fairly well, but in this book the word will always be used in the technical sense as here defined.

8. When Work is Done, Energy is Transferred.—After the work is done, a certain definite effect has been produced, and for producing this effect a certain definite amount of work was required. Thus, in lifting a stone, one may use a long lever or a short one. If the long lever requires but one third the force, it requires that the hand should move through three times the distance to raise the stone to the same height. The product of the force by the distance is the same in either case, and this is found to be true whatever mechanism is employed to produce the result.

When the stone has been raised, it possesses the power to do a certain amount of work. By a series of levers or pulleys it may raise another stone, or it may fall back to the ground and produce a certain amount of heat. The work which it can do is precisely equal to that which has been done upon it, and this ability to do work is called its Energy.

9. Kinetic and Potential Energy.—A body may posssess energy, or the power to do work, by reason of its position—as the stone raised above the ground—or because it is bent and trying to spring back, like a coiled watch-spring. In such cases its energy is called Potential Energy. Again, it may possess energy because of its motion. A moving train of cars possesses energy and will not stop until it has given up this energy by doing work. It may do this by evolving heat when the brakes are applied, or it may do it by running up a grade, by which its energy of motion is converted into potential energy; but it must in some way do an amount of work just equal to its energy before it can stop. Energy due to motion is called Kinetic Energy.

When a ball is thrown vertically into the air, it has, at its highest point, energy due to its elevated position. As it falls its potential energy gradually disappears, but its velocity, and therefore its kinetic energy, is increasing; just before it strikes the ground, all its energy is kinetic. When it strikes the ground and comes to rest, its energy is all converted into heat, which is only another form of (kinetic) energy.

Thus whenever anything loses energy it does so by giving it to some other body, and the amount lost by the one is exactly equal to that gained by the other.

10. Conservation of Energy.—The whole amount of energy in the universe can be neither increased nor diminished.

This law is called the law of Conservation of Energy. It is a general statement which no fact is known to contradict, while it agrees with the result of many careful experiments. The law is believed with much confidence by all scientific men.

11. Friction causes an Apparent Waste of Energy.—In all the illustrations that I have given, there were certain apparent losses of energy due to friction. The ball thrown into the air returned with a velocity less than it had in rising. Friction always lessens the apparent energy of a body and always produces heat. It was a most important step in the proof of the law of conservation of energy to show that heat was itself energy, and that a definite amount of heat, therefore, corresponded to a definite amount of kinetic or potential energy in its more evident forms. This proof, begun by Rumford and Davy, was made invincible by the experiments of Joule,* who showed that by whatever

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*Joule. Phil. Mag. Ser. 3, vols. 23, 26, 27, etc.

process the heat might be produced, to produce any given amount the same amount of visible energy must be used up.

12. The Mechanical Equivalent of Heat.—One pound must fall from a height of 778 * feet to produce the heat necessary to warm one pound of water one degree Fahrenheit. It has also been shown that the heat necessary to warm a pound of water one degree will, if used in an engine, raise a pound weight 778 feet. The work done when a pound is raised one foot is called a foot-pound: the heat necessary to warm a pound of water one degree is taken as a unit quantity of heat (or "unit of heat"); therefore a unit of heat is equivalent to 778 foot-pounds, and 778 is called the "Mechanical Equivalent of Heat" or "Joule's Equivalent."

13. Work may be Positive or Negative.—In case a body moves contrary to the action of a force, that force is doing a negative amount of work; thus in raising a weight, the hands do a certain amount of work equal to the product of the weight by the height through which the weight is raised. If now the weight is lowered again, the hands do a negative amount of work, and when the weight has reached its original place, the negative and positive amounts of work are equal and no work has on the whole been gained or lost. The difference between the ordinary and the technical uses of the word in this case is very apparent.

14. Measurement Requires the Use of Units.—It thus appears that there are many quantities in Physics which must be measured. We shall find many more. The way

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* The value 778 found by Rowland in 1879 is probably much more accurate than the value 772, given by Joule, and has been shown by Rowland to represent Joule's own experiments very well. The energy of a body raised above the earth is equal to the product of its weight by the height to which it is raised, and therefore depends upon the intensity of the earth's attraction at the place,

we measure a thing is to compare it with some standard which is chosen as a unit. Thus, to measure ten yards of rope, a yard-stick is taken and applied ten times. To weigh out ten pounds of sugar, a pound weight is ten times balanced against a sufficient quantity of sugar, or a weight ten times as heavy may be used once.

It is not necessary, however, to have a new and independent unit for every new thing to be measured; thus in measuring a volume of water, we might express the amount in gallons, or we could state it equally well in cubic feet, using a standard of volume derived from the linear standard.

There are so many quantities in Physics that must be measured that it is very desirable to have as few standards or fundamental units as possible, and to derive all others from these, and a little consideration will show how this may be accomplished.

15. Measurement of Quantities in the C. G. S. System.—The units upon which all other units are based are the centimeter (or one-hundredth part of a meter), as the unit of length; the gram, as the unit of mass; and the second, as the unit of time; and the system which is based upon these units is called the "centimeter-gram-second (or C. G. S.) system."

We may apply this system of measurement to the quantities just discussed, viz., velocity, acceleration, force, and energy.

Velocity is found by dividing the space traveled by the time spent,* and may be measured in miles per hour or per minute. In the C. G. S. system it is measured in centimeters per second, and the unit of velocity is a velocity of one centimeter per second. There is no special name for this unit.

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* Of course it is not the time, but the number representing the time, which is the divisor in such cases.

16. Dimensions of Units.—Just as we speak of a solid as having three dimensions of length, or L^3, so we may speak of a velocity as having the "dimensions" of $\frac{L}{T}$, or LT^{-1} (length divided by time).

Forces, again, produce change of velocity. The rate of change of velocity (or acceleration) is found by dividing the velocity acquired at a uniform rate by the time spent in acquiring it. Therefore acceleration is measured by velocity divided by time, and its dimensions will be $LT^{-1} \div T$, or LT^{-2}.

The amount of force which produces this motion is found by multiplying the acceleration by the mass of the moving body. The dimensions of force are therefore $LT^{-2} \times M$, or MLT^{-2}.

We find that, just as we may measure volumes in terms of feet, so we may build up a unit out of the units of length, mass, and time, for measuring velocities and forces.

Similarly, work or energy is measured as the product of a force multiplied by a length, and the dimensions of energy are $MLT^{-2} \times L$, or ML^2T^{-2}.

The unit of force, in the C. G. S. system, is called the dyne. It is the force required to impart a unit velocity in one second to a mass of one gram. It is a trifle greater than the weight of one milligram.

The unit of work or energy in the C. G. S. system is called the Erg. It is slightly greater than the work done in raising a milligram through one centimeter.

CHAPTER I.

ELECTROSTATICS, OR ELECTRICITY AT REST.

17. Electrification by Friction.—If we rub a stick of sealing-wax, or a hard-rubber penholder or comb, with a piece of dry flannel, on holding it near some small shreds of tissue-paper or bits of thread or straw, they will fly up and adhere to it: after a time they will fly off.

The ancients knew that amber and tourmaline had this curious property, and the science receives its name from amber (ἤλεκτρον).

The list was not enlarged until about 1600 A.D., when Gilbert, an English physician and scientist, found that the same property was possessed by quite a number of substances.

Lay a sheet of well-dried paper on the table and rub it briskly with a brush or a woolen cloth. The sheet will now adhere to the table, and if taken up and laid against the wall of the room, will stick there a minute or so.

In all these experiments with frictional electricity it is necessary to have things perfectly dry. If the air is at all moist the experiments may fail entirely. Glass, flannel, paper, and all hygroscopic substances usually require to be dried by artificial heat to make them work properly.

18. Repulsion and Attraction.—Take two sticks of sealing-wax or two hard-rubber rods. Rub one of the rods with a woolen cloth and hang it up in a wire stirrup, suspended by a thread so that it may be free to turn. (Fig. 1.) Rub the other rod and bring it near the first.

There is evidently a repulsion in place of the attraction previously observed. Use two glass rods rubbed with silk, and the same results are found.

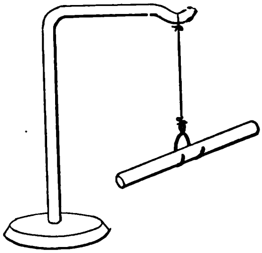

FIG. 1.

Rub the rubber rod with flannel, hang it up and hold near it the glass rod which has been rubbed with silk. These rods attract each other.

It is plain that the state of the two rubber rods must be the same, also that of the two glass rods. The experiment shows that the glass rod and the rubber rod are in a different state.

Definition.—When anything acquires these properties of attraction or repulsion it is said to be electrified, or charged.

Definition.—When glass is rubbed with silk it is said to have a positive charge, as is any body which has the same kind of charge. Any body electrified in the opposite way is said to have a negative charge. The rubber rod in the above experiment was negatively electrified.

19. First Law of Electrostatics.—The facts of attraction and repulsion are generally expressed by saying that bodies oppositely electrified attract each other, and similarly electrified repel each other. This statement involves no theory as to the nature or method of the force. An endeavor to explain these will be made later.

20. Conduction.—Hang up two small corks or balls of pith by two silk threads, so that they just touch each other (Fig. 2). Rub the sealing-wax as before and hold it against the balls. On taking it away they will fly apart. We thus see that bodies may become electrified without being themselves rubbed. The flying off of the particles in the first experiment is thus explained.

Again, place a tin cup on a cake of paraffin, and draw the electrified rod over the cup. A pith ball held by a silk thread near the cup will be first attracted and then repelled, showing that the cup is charged. Touch the cup and its charge disappears.

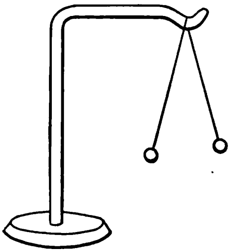

FIG. 2.

The charge can thus pass from one body to another, or from one part of a body to another, by conduction. When the cup was touched its charge disappeared. The hand therefore has the power of conducting the charge. That the cup remained charged until it was touched shows that paraffin has not this power.

Definition.—Bodies that conduct well are called conductors; those that conduct slightly or not at all are called non-conductors or insulators.

Faraday showed that this difference is only a difference in degree. All bodies conduct somewhat (gases at ordinary temperatures seem to be perfect non-conductors), and all oppose some resistance to the flow of electricity.

In the following list, the conducting powers become less toward the bottom.

Substance.	Relative Conducting Power.
Silver	1 000 000 000.
Mercury	16 000 000.
Gas-carbon	400 000.
Sulphuric acid—dilute	160.
Gutta percha	.00 000 000 000 4.

21. Induction.—Place two tin cups on cakes of paraffin, and let the cups be in contact. An electrified rubber rod is held near one cup, and while it is held there the two cups are separated (Fig. 3). A pith ball suspended by a silk thread is charged by the rubber rod. On bringing it near the cups, it will be attracted by one and repelled by the other. The cup farther from the rod will be charged like the rod (negatively), while the nearer one will have the opposite charge.

In separating the cups, they must not be touched by the hand or they will be discharged. Move them by the wax blocks on which they stand. The gold-leaf electroscope (see below) may be used to test their charges instead of the pith ball, and is much more sensitive.

From this experiment we learn that a charged body not only repels a similarly charged body, but repels the charge itself, causing a like charge to appear in the farther parts of a neighboring conductor, and an unlike charge in the nearer parts. (When the two cups are touching each other they are electrically one body.) The same thing takes place in one cup as in two, but on removing the rubber rod the charges flow together and disappear. Whenever material objects are attracted or repelled, it is only because the charges which they possess are attracted or repelled. "The power which electricity . . . possesses of causing an opposite electrical state in its vicinity has been expressed by the general term Induction." * It accompanies and modifies nearly all electrical phenomena.

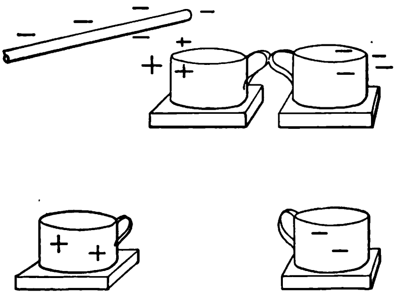

FIG. 3.

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* Faraday. Experimental Researches, vol. I. p. 1.

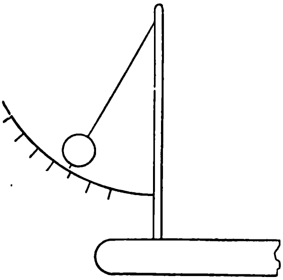

FIG. 4.—PITH-BALL ELECTROMETER.

22. Electroscopes.—The one property which we have so far found as belonging to electricity at rest is attraction or repulsion. Its power to flow through certain bodies is shown only when in motion, and all the other properties which we shall find in the feeble spark, the flash of lightning, or the express train drawn by the electric motor, are due to the motion of the electricity. All instruments, therefore, for detecting the presence of a charge must be based upon this property of attraction and repulsion.

Early instruments consisted of hanging threads, which were attracted by any electrified body; a straw balanced upon a needle-point, free to turn easily when the charged body was held near one end; a pith ball hung by a thread from the top of a wire (which also served to roughly measure the amount of charge by the distance to which it was repelled from the wire).

23. Gold-leaf Electroscope.—Of this class of instruments, the gold-leaf electroscope is by far the most delicate, and is a very useful piece of apparatus. It consists of a glass flask or receiver, through whose stopper passes a brass rod or stiff wire. This rod terminates at its upper end in a ball or a plate also of brass; while from its lower end hang two thin strips of gold-leaf. Whenever a charged body is brought near the electroscope, an induced charge is given the gold-leaves, and, being charged alike, they repel each other and fly apart.

It is a valuable exercise for each student to construct a gold-leaf electroscope. Procure a rather short wide-mouthed bottle (see Fig. 5), and fit a plug of hard paraffin to the mouth, for a stopper. Solder a thick piece of wire to a smooth disk of tin or zinc, two inches in diameter. File the other end of the wire to a chisel edge, and fit it to the paraffin stopper so that it may pass through it as shown in the figure. Fasten two long narrow strips of gold-leaf to the sharp edge of the wire by a little mucilage. The strips may be long enough to touch the sides of the bottle when wide open, if the bottle is provided with tin-foil as explained below. As gold-leaf is quite hard to manage, two strips of aluminium-leaf may be used instead.

The instrument is more sensitive and useful if a strip of tin-foil, ¾ of an inch wide, is run down one side of the bottle, inside, across the bottom, up the other side, and down the outside of the bottle so as to touch the table on which the electroscope stands. The gold-leaf strips should be turned so that when charged they will fly out and touch the tin-foil; this will discharge them and prevent their tearing.

FIG. 5.—GOLD-LEAF ELECTROSCOPE.

24. Experiments with the Electroscope. — Excite the rubber rod and bring it toward the electroscope. The negative charge in the rod induces a positive charge in the disk, and a negative in the leaves, which causes them to stand apart. Touch the disk. There is now a positive charge in the disk, but the negative is in your body or in the ground, and the leaves are collapsed. Remove your finger and then the rod. The positive charge in the disk

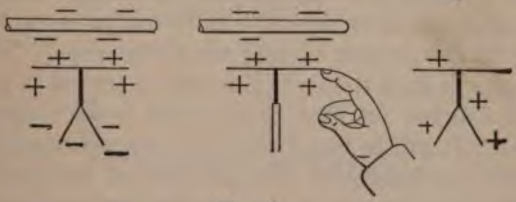

FIG. 6.

now distributes itself over the instrument and the leaves diverge again.

With the electroscope thus charged we can tell whether any other body is positively or negatively charged. If a positive charge is brought near, the leaves open wider; if a negative charge, they come together. If the negative charge approaches still nearer, they again diverge. All these effects are readily explained when the theory of induction, as illustrated in charging the electroscope, is clearly understood.

25. Distribution of Charge.—If a body is a good conductor of electricity, the charge is free to move about and reach a state of equilibrium, just as water, poured into a dish, will flow about until it is level, when it comes to rest. But when the charge has come to rest (which is almost immediately) it is not equally strong everywhere. This may readily be tested by the gold-leaf electroscope and the "proof-plane," which is simply a metal disk (a cent) stuck on the end of a slender rod of hard rubber.

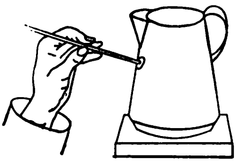

FIG. 7.

Give a charge to a tin cup on a cake of paraffin. Lay the proof-plane successively on different parts of the cup, testing its charge each time by the electroscope. The cent gets a charge each time which may be regarded as a sample of that existing on that part of the surface where it is touched. It will be found that the strongest charge will be given the proof-plane on the outer part of the handle and, in general, on any part of the cup that projects beyond the rest. A tin plate or pan, similarly tested, will have the strongest charge on the edges, while the middle of the pan will have but a very weak one.

26. The Charge on a Conductor is all on the Outer Surface.—If investigation is extended to the inside of a rather deep cup, it will be found that, no matter how strong a charge may be given the cup, no charge at all can be found on the inside of the cup, except near the top. The smaller the opening the more nearly does this become true, and inside a closed vessel there is no charge whatever. (This is not true if there is a charged body inside the vessel.)

The cup in these experiments may be charged by induction from a rubber rod, as was the gold-leaf electroscope (Fig. 5). A stronger charge may be given it by the electrophorus or the electrical machines, to be described later. Instead of the tin cup or pan, the insulated brass cylinders, ordinarily sold for the purpose, may be used if the lacquer is first scraped from the parts which are to be tested. The tin cup should be free from any sharp points, and the proof-plane, if made of a disk of metal instead of a cent, must have its edges carefully rounded.

Coulomb * was the first one to show by careful experiments that all the charge resides upon the surface of a conductor. The important fact may be tested in a number of different ways and has been made a subject of thorough investigation, as it affords the best proof of the law of electric attraction and repulsion (p. 43). Thus, if two hemispherical shells are provided with insulating handles and closed over a charged insulated ball, they remove from the latter all its charge.

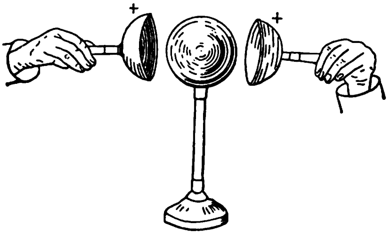

FIG. 8.—BIOT'S EXPERIMENT.

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* Coulomb. Mémoires de l'Acad. 1786.

Again, if the gold-leaf electroscope is placed within an insulated wire cage, no matter how strongly the latter may be charged, the leaves cannot be made to diverge.

Faraday,* to fully assure himself of this, constructed a large insulated cage, covered with paper and tin-foil, and, going inside of it, caused it to be charged strongly by the great electrical machine of the Royal Institution; but his gold-leaf electroscope, and all other apparatus which he carried in, failed to show any sign of a charge within the cage, though abundant sparks from the exterior proved it to be thoroughly electrified.

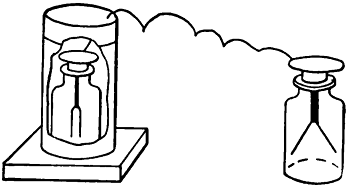

FIG. 9.

Similarly, if any charged body is put within a cup or other closed conductor and is touched to it, the two are electrically one, and the whole charge flows to the outer surface, completely discharging the inner body.

27. The Effect of Points.—An interesting result of the irregular distribution of the charge is seen in the case of points. Franklin † was the first to discover and apply this effect, and he gives

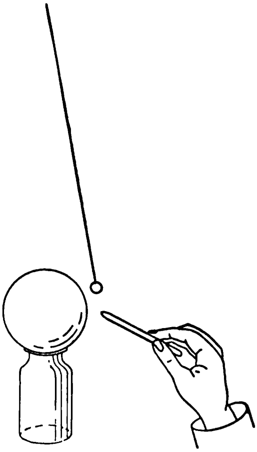

FIG. 10.

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* Exp. Res., vol. I. p. 366.

† Sparks' Life of Franklin, vol. v. p. 181.

the following experiment to illustrate it. Suspend a pith ball by a thread, so that it shall rest lightly against an insulated conductor. Charge the conductor so that the pith balls shall fly out two or three inches. Take a needle in the hand, and present its point to the charged body. Before the point reaches the conductor the pith ball will fall toward it, showing that it has been partly discharged. Again, fasten the needle to the conductor with the point projecting outward. It will now be found impossible to charge it, as the needle discharges it as fast as the charge is given. In the one case the induced, and in the other the direct charge accumulates on the point so strongly that the air is unable to stand the pressure and the charge flies off.

Franklin's practical mind * led him to apply this discovery in such a way as to bring him immediate and lasting renown, such as has been accorded to but few. As a scientific man his attention had often been called to the similarity between lightning-flashes and the electric sparks which in his laboratory had so engaged his attention. The similarity had indeed been speculated upon by others, but he saw that in the power of points to " draw off the electric fluid " he was provided with a means of deciding the question whether the similarity was real or only apparent.

There was at that time no spire in the city of Philadelphia, but as one of the churches was about to erect one, he conceived the idea of placing a pointed rod at its top,

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* As showing this practical tendency I quote the following : "Nor is it of much importance to us to know the manner in which Nature executes her laws; it is enough if we know the laws themselves. It is of real use to know that China left in the air unsupported will fall and break, but how it comes to fall and why it breaks are matters of speculation. It is a pleasure indeed to know them, but we can preserve our China without it." (Sparks' Life of Franklin, vol. v. p. 284.)

leading the other end of the rod to a sentry-box where a man might be stationed to experiment upon the forces there displayed.

Pending the erection of this spire, it occurred to him that a kite might take the place of the building as a support for the metal point, the kite-string taking the place of the leading wire. Making a kite of two sticks and a silk handkerchief, he fastened a wire to the upright stick and attached a hemp cord for holding the kite.

On the first appearance of a thunder-storm he went out with his son (twenty years of age) and flew the kite. To the end of the hemp cord he fastened a key, while a silk ribbon afforded a suitable insulator by which he could hold the cord.

Standing under a shed, he anxiously awaited the result. His anxiety increased as a cloud passed by with no appearance of electricity, when he noticed a sudden standing out of the fibres of the cord. Presenting his finger to the key, he received a spark. Repeated sparks were taken, a Leyden jar was charged, and all the experiments usually performed with electricity were successfully tried.

In the mean time his letters, containing an account of his proposed experiments, had been published in England and translated into French. They excited much interest in France, and the experiment was tried by means of a high pole carrying a pointed conductor, and with the same success as his own attempt. The first French experiments were about a month earlier than his own, but, being performed in accordance with his own suggestions, they detracted nothing from the originality or honor of his own discovery, which was made before the news of the French experiments had reached America.

28. Quantity of the Induced Charge.—Having noticed the general phenomena of conduction, induction, and distribution of the charge, it is necessary to examine the amount of charge produced in different cases.

Set a tin cup upon a cake of wax. Connect it by a wire three feet long to the electroscope. Suspend a metal ball by a silk thread. Charge the ball and slowly lower it into the cup. The gold-leaves diverge more and more until the ball is fairly within the cup; after this they remain stationary however the ball may be moved about. Bring the ball to the side of the cup and notice the effect as the ball touches the cup: there is no effect. The ball is found, however, to be entirely discharged.

It is evident that the charge upon the ball, which we will assume to be positive, induced a negative charge upon the inside of the cup and a positive charge upon the outside of the cup and on the electroscope. Further, it is evident that the charge upon the inside of the cup was just sufficient to neutralize the charge on the ball and no more; so that when the ball touched the side of the cup its charge was neutralized by that on the interior of the cup and no effect could be seen on the electroscope; in other words, these two charges were just equal.

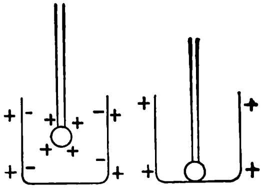

FIG. 11.

If the same experiment is tried, but the ball is removed without letting it touch the cup, the leaves collapse and become as they were before the charge was introduced. Hence the charges upon the outside and inside of the cup are just such as to neutralize each other. These charges are, therefore, all equal in amount—that on the ball, that on the inside, and that on the outside of the cup.

29. Faraday's Ice-pail Experiments.—These experiments were first performed by Faraday, who used a pewter ice-pail in place of the tin cup; and they are commonly known as Faraday's Ice-pail Experiments.

He also showed that four ice-pails, one within the other, but insulated from each other, might be used instead of one. If the outer one be connected to the electroscope, and the charged ball lowered into the inner one, the same results are seen as with one pail: each pail induces upon the next, charges just equal to its own, so that the charge on the outer surface is the same as when one pail is employed.

30. Equality of Charges Produced by Friction.—These experiments provide us with an excellent means of ascertaining the equality of positive and negative charges, for any charge placed inside the hollow conductor immediately produces an equal charge upon the outside of the conductor, wherever in the interior it may be placed; while if two equal and opposite charges were to be placed in the interior the external effect would be zero, as the external charge is the algebraic sum of the two charges inside.

Attach a piece of fur to a hard-rubber handle. Holding it by this handle, rub it upon a rod of hard rubber and present the fur and the rubber rod successively to the electroscope. They are found to be oppositely charged.

Introduce each in succession into the tin cup connected with the electroscope, and the charges will be found to be nearly equal (the fur must be introduced quickly, as it soon loses its charge even when insulated, because of the points with which it is covered).

Discharge both the rod * and the fur. Introduce them into the cup and there rub them together. No movement of the gold-leaves will be observed. If either the fur or the rubber rod is withdrawn, an immediate divergence of

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* Rubber, glass, etc., are most readily discharged by passing them through or over the flame of a Bunsen lamp.

the leaves takes place due to the charge upon the body remaining inside the cup.

Hence the two charges produced by friction are opposite in kind and exactly equal in amount, as was the case when the charges were produced by induction.

There is no known method of producing one kind of charge without the other, or of producing more of one than of the other.

CHAPTER II.

ELECTRICAL MACHINES.

31. Frictional Machines.—The early machines made use of friction to produce electrification; a ball of sulphur turned by a crank and rubbed by the hand, or later by a rubber pad; globes, cylinders, or disks of glass rubbed by leather on which was spread a mixture of mercury and tin—these have in turn been employed; so also the friction of steam and fine drops of water issuing from a steam-boiler through narrow orifices. All these devices are of hardly more than historic interest at present, as electric induction may be made a much more ready and abundant means to the same end.

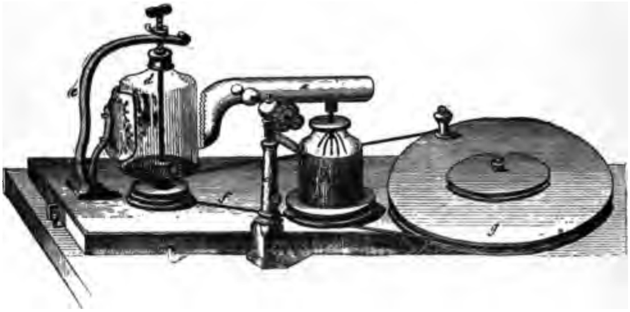

FIG. 12.—EARLY ELECTRICAL MACHINE.

32. The Electrophorus.—The electrophorus is the father of all the modern machines, and is easily understood. It consists of a metal plate or pan, containing a cake of some kind of resin. A metal cover is provided with an insulating handle by which it may be lifted off the resin-cake.

A tin pie-plate filled with hard paraffin serves excellently; another plate, somewhat smaller, forms the cover, and should have a hard rubber rod for a handle.

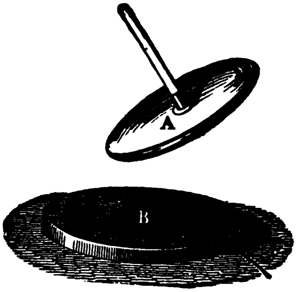

FIG. 13.

To use the electrophorus, beat it with a cat-skin until it is well charged. Place the cover upon it and touch the finger to the cover. A sharp snap will be noticed. Now lift the cover by its handle, and it will be found strongly charged. Discharge the cover by touching it, and replace it upon the cake as before. Touch it and raise it by the handle, and a charge will again be found upon it.

The explanation of the action is as follows: When the cover is brought near to the charged cake a positive charge is caused to appear in the lower part of the cover by induction, and a negative charge in the upper part. Or if the finger is placed on the cover, a positive charge appears in the cover and a negative charge passes off through the body to the ground.

At first sight it might seem as if we had a method of getting something from nothing, but more careful examination will correct any such idea. With a sensitive spring-balance measure the apparent weight of the cover as it is lowered down to the cake, and again as it is raised up after being touched by the finger. The force is greater as it is raised, and the difference between the two weights measures the force required to overcome the attraction of the charges, and shows that work must be done to raise the cover on account of its charge. This is the source of the energy of the charge.

In dry weather the cake loses its charge very slowly, and it may be used without recharging for a number of days.

33. Toepler-Holtz Machine.—For supplying electricity in greater quantities the Toepler-Holtz machine is a form which is much used. This machine, shown in Fig. 14 and illustrated by the diagram Fig. 15, has two glass plates; the back one *e'* is stationary and is slightly larger than the front one *e*, which is mounted on an axle and can be set into rapid rotation.

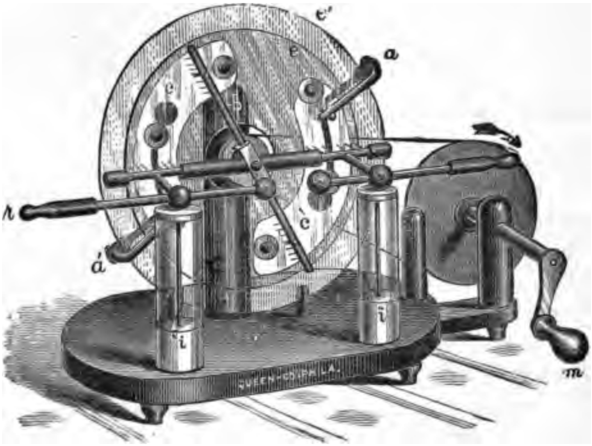

FIG. 14.

On the back of the fixed plate are two pieces of tin-foil, *c*, *c'*, called inductors, over each of which a paper is pasted to prevent the charge from escaping from the sharp edges. Each of these inductors is connected by a curved metal arm *a*, *a'* to a tinsel brush which lightly touches the buttons on the front of the revolving plate. These buttons are of metal, and each is attached to a disk of tin-foil, which is pasted to the front of the plate. Besides this there is a pair of combs on a horizontal rod, insulated from each other and from the table, and a diagonal metal rod *b*, carrying a comb on each end. The positive and negative charges are drawn from the horizontal combs. To understand the action of the machine, we will suppose these combs to be temporarily connected by pushing in the handle *r* until the balls come together, and, for the present, will suppose the diagonal bar *b* to be entirely removed.

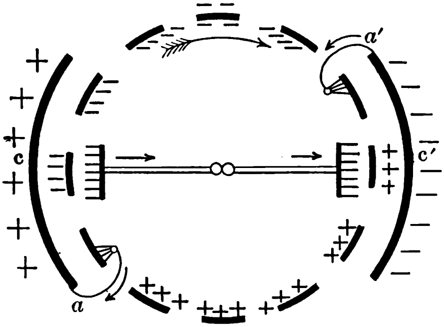

FIG. 15.—DIAGRAM TO ILLUSTRATE THE OPERATION OF THE TOEPLER-HOLTZ MACHINE. THE ARROWS SHOW THE DIRECTION OF FLOW OF THE POSITIVE CHARGE.

Let a small charge, which we will suppose to be positive, be upon the inductor *c*. This charge acts inductively upon the combs and the tin buttons as they pass by. Since the charge is very strong upon the points of the combs, there is a constant giving way here, a discharge taking place into the air, and hence we may consider the combs to be electrically connected with the buttons as they pass by. By the inductive action of the positive charge on the inductor *c*, the comb becomes positively and the buttons negatively charged.

As the plate and its negative buttons reach the brush connected to the inductor *c*′, a flow takes place through the brush and off from the inductor; and because the button is between the brush and the inductor, the button is almost completely discharged, as though it were within a closed conductor (see p. 17); so that no matter how strong the charge upon *c*′ or how weak that upon the button, *c*′ will still take more charge from the button. When the button reaches the right-hand comb, the same action takes place as at the left. The inductive action of *c*′ causes the comb to be negatively and the button to be positively charged. The button goes on to the left side of the machine, gives up most of its charge to the brush and inductor *c*, and is again charged negatively at the left comb.

It is clear that a small initial charge is all that is required to start the machine. This charge is produced by the friction of the tinsel brushes on the buttons. No matter how small this charge may be, it rapidly increases, and the limit is soon reached where the loss from leakage just balances the supply.

In this explanation the diagonal comb has been omitted, and it is not active so long as the horizontal combs are connected. Now suppose *r* to be drawn out as shown, leaving the combs insulated from each other. They will then become strongly charged; it will become very difficult to charge them any more, and the inductor *c* will no longer have power to cause any further flow from the buttons to the comb as they pass by. Hence whatever positive charge was not drawn off by the brush will pass the comb and be given up to the inductor *c*′, from which also a small negative charge will be at the same time received. This will be in the same way given to the inductor *c*, and the action continued until the inductors will both be discharged; indeed the charges will be actually reversed so that *c* will become negative and *c*′ positive. To prevent this action the diagonal bar is added. Now if the buttons pass the horizontal combs without getting the proper charge they will receive the proper charge at the combs on the end of the bar *b*. These combs are always connected together, and one receives a positive charge as the other receives a negative; hence they never become strongly charged, and the inductor is, therefore, always able to give the proper charge to the buttons.

The primary combs always have the first offer of charge from the buttons. If they decline to receive it, being already supplied, then the combs on *b* kindly appropriate what is left and enable the buttons to dispose of the charge which would weaken that on the inductors, while they at the same time give in exchange a charge which strengthens that on the inductors and keeps up the action of the machine.

On the front of the machine are two small Leyden jars *i* and *i′* (to be described on p. 44). When these are lacking, a constant stream of sparks goes across the gap between the knobs connected to the horizontal combs. If the jars are in place, no spark passes till they are fully charged, when it suddenly jumps across, leaving the jar nearly discharged. These sparks are therefore much brighter and louder than when the jars are removed, but the whole quantity passing is not very different.

34. Wimshurst's Machine.—Another machine which is much used at present is Wimshurst's (Fig. 16). In this machine also there are two plates, but these revolve in opposite directions, and both are provided with strips of tinfoil, as shown in the figure. The machine is provided with two diagonal rods, one for each plate, with brushes at both ends. These rods and brushes put the opposite strips on each plate in electrical connection once in each revolution. Suppose, as before, that there is a small charge on the strips of one plate, *A*. This acts inductively on the strips of *B* while they are cross-connected by the brushes. The charge which the *B* strips thus acquire acts inductively on the strips of *A* while these are cross-connected. Thus each plate acts as inductor to the other, and a succession of charged strips passes the combs.

It is to be noted that none of these machines produces electricity. Their office is much more like that of a pump which carries water from one place to another. The electrical machine draws off from one knob whatever the other knob acquires. This was observed by Franklin, who remarked: "We know that the electric fluid is in common matter because we can pump it out by the globe or tube."

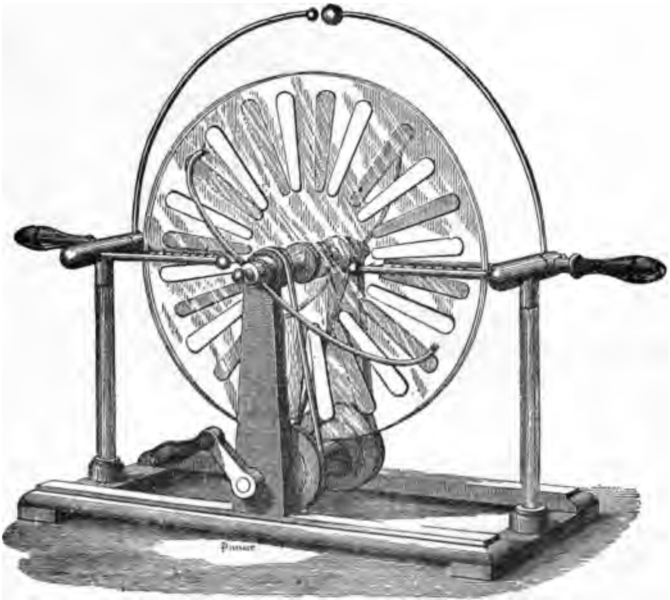

FIG. 16.

CHAPTER III.

EXPLANATION OF PHENOMENA—ELECTRICAL THEORIES.

35. Theories of Electricity.—What is electricity? Is it one thing or two things? Is it matter or energy or neither? These are some of the questions which have often been asked concerning it, and the answers have been far from complete. There have been supporters of the "two-fluid" theory and the "one-fluid" theory, and the adherents of each have done much to advance our knowledge of the science. Franklin held * that there was one fluid; that charged bodies were surrounded by an electrical atmosphere, wherein their charge consisted, and that the total quantity in existence did not change, "the abounding of fire" in one body being equal to "the wanting of the other."

Faraday experimented carefully to produce more of one kind than of the other, but found, as we have already seen, that whether called into existence by friction or induction or in any other way, the amounts of the positive and negative charges were precisely the same.

His mind seems to have been in remarkable sympathy with nature, so that he grasped her methods of action and marked out a path for future experiments, even when the proofs to which he appealed were far from conclusive. To him it seemed improbable if not impossible that one body should act directly upon another at a distance of a

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* Sparks' Works of Franklin, vol. v. pp 189 and 198.

foot or an inch through empty space, or without some medium by which its action could be communicated.

36. Induction Takes Place in Curved Lines.—He felt confirmed in this view, so far as charged bodies are concerned, by finding that induction seems to proceed along curved lines.

To test this fact he fastened a solid shellac cylinder by one end to a wooden base. The upper half of this rod is rubbed by a flannel cloth; and a metal plate 2 inches in diameter is laid on the end of the rod (see Fig. 17). A small ball or bead of metal on an insulating handle is put at different places, as at *g*, and touched for a moment with a knitting-needle. It is then tested by the electroscope for a charge. If there is any electrical force at the point where the bead is placed, there will be an induced charge given to the bead by this process.

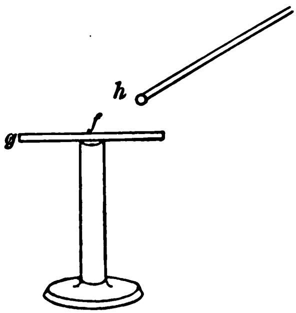

FIG. 17.

When the bead is placed under the edge of the plate, or at *g*, such a charge is found. At *f* no such charge is produced, hence the induction does not act through the plate, but at *h* a charge is again observed. Hence the force must have acted in curved lines around the edge of the plate as shown in the figure.*

Much more conclusive is the additional fact, noticed by Faraday, that the amount of induction depends on the nature of the insulator through which the induction takes place. This he proved by laying a block of sulphur on top of the metal plate, when a stronger charge than before was

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* Exp. Res., vol. I. p. 382.

obtained at *h*. The presence of the sulphur is thus found to increase the effect, showing plainly that the induction is affected by the nature of the medium.

37. Faraday's Theory of Lines of Force.—Faraday's idea, therefore, was that a charged body throws the surrounding medium into a polarized condition along certain lines (lines of force *), and that the electric induction of one body on another is exerted by means of this polarization. Along these lines he supposed a tension to exist, while the lines themselves repelled each other and therefore spread out as much as possible. Thus he says †: " The direct inductive force, which may be conceived to be exerted in lines between the two limiting and charged conducting surfaces, is accompanied by a lateral or transverse force equivalent to a dilatation or repulsion of these representative lines. . . . Induction appears to consist in a certain polarized state of the particles, into which they are thrown by the electrified body. . . . It constitutes charge in every ordinary case and probably in every case; it appears to be the cause of all excitement and to precede every current."

The form which these lines of force assume in some special cases is clearly shown in the diagrams p. 38. The lines of force start from all charged bodies, pass through the insulating medium and terminate upon opposite charges, equal in amount to those from which they start; thus they never stop or " fade out " when radiating from a charged body until they end upon the corresponding opposite charge.

Acting upon these suggestions of Faraday, Maxwell undertook the mathematical investigation of the subject

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* It is not necessary to suppose that these lines of force have any actual existence as lines. We have no direct evidence of such existence; but they serve to aid in forming a convenient mental image of what is taking place, just as we use the idea of rays of light in optics, though light actually travels in waves rather than in rays.

† Exp. Res., vol. I. p. 409.

and showed * that such a tension along the lines of force combined with a repulsion or pressure at right angles to them is sufficient to explain the forces of attraction and repulsion which are observed to take place between charged bodies.

38. Electricity and Light.—It was one of the great objections to the wave theory of light that it required all space to be filled with a medium specially fitted to carry it, and now to fill space over again with a new medium seems highly objectionable. But recent investigation has proceeded to a remarkable extent along this line, and not only has the existence of a medium been established, but this medium has been shown to have many of the same properties which are known to belong to the luminiferous ether, making it highly probable that the two are closely connected, if not the same thing.

Faraday himself suggests † that light may be a vibration of lines of force; and again,‡ "such an action (the transmission of magnetic force) may be a function of the ether; for it is not at all unlikely that, if there be an ether, it should have other uses than simply the conveyance of radiations."

39. Nature of the Luminiferous Ether.—Let us see what is known of the nature of ether as shown by optical phenomena.

Light is a vibration carried from one place to another by the elasticity of the medium which is vibrating. Sound is a similar vibration; but while a sound-wave consists of successive condensations and rarefactions, the facts of polarized light show that light is a "transverse" vibration, i.e., the vibrating particles move at right angles to the direction of the wave, as do the water-particles in a wave on the surface

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* Maxwell's Electricity and Magnetism, vol. I. p. 148.

† Exp. Res., vol. III. p. 451. ‡ Ibid., p. 331.

of water, or the parts of a rope when a wave is sent along the rope by shaking it.

This means that the vibrating substance must be stiff enough to fly back very quickly when bent or twisted. We are therefore driven to the conclusion that this medium (the luminiferous ether) is a jelly-like substance; indeed it is quite a stiff jelly, so that when drawn aside it jumps back very rapidly indeed. Then, too, this jelly must permeate all bodies, since all allow to some degree the passage of light. The nature of this jelly is, however, affected by the nature of the body in which it is diffused, so that it seems to be much less rigid (or more dense) in most transparent bodies than in air; while in the metals it has so far lost its stiffness that, when it is moved to one side, it makes no appreciable effort to spring back: and since an elastic stiffness is required for light vibrations, metals are by their nature * opaque.

From electrical considerations Faraday was led to think that while in metals a flow of electricity is accompanied by no tendency to flow back on removing the force, yet whenever a body is charged, a flow takes place in the medium about the charged body, and as soon as the force is removed the medium returns to its original position.

40. Theory of an Electrical Medium.—For reasons that will appear more fully as we go on, the following ideas have found wide acceptance.

The medium required by Faraday's theory is believed to be closely connected with the luminiferous ether. It pervades all transparent substances as a jelly, but in metals has lost its stiffness and is much more like water. Since

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* Some substances, like snow, pulverized glass, and wood, are opaque because of their granular or cellular structure, while the material of which they are composed is fairly transparent. The opacity of metals is much greater, and is due to the nature of the material itself.

the planets move through this medium with no appreciable friction, we must suppose that it yields readily to this comparatively slow motion, while to the much quicker vibrations of light it is very elastic and stiff; just as a barrel of tar, laid on its side, will flow like a liquid if given time enough, while if struck by a hammer it will break. Similarly if water is struck a quick sharp blow by the open palm, the hand will sting, while a slow blow produces no such effect.

Charging a body consists in imparting to it more of this medium than it commonly possesses—or in taking away from the body some portion of the medium which commonly permeates it. As subtraction may conveniently be considered as the addition of a negative amount, and as it is awkward to describe both processes, I shall ordinarily speak of a charge as consisting in adding to the normal amount of electricity in a body.

41. The Medium is Incompressible.—The medium, however, acts as if it were entirely incompressible. Whenever an additional quantity is given to any body there is an immediate pressing out of the medium in the neighborhood of the charge, just equal to the amount imparted to the body.

We know that if a charge is given to a body which is connected to the ground by a wire there will be a flow along the wire just equal in amount to the charge given, and all evidence of any charge immediately disappears. If, however, the conductor is everywhere surrounded by an insulator like air, the same amount of flow takes place in the air away from the charged body as before, but with the important difference that, as soon as the force is removed, the medium will spring back again. We no longer have a motion which is resisted by friction only, as is the flow in a conductor, but a displacement which is resisted by the elasticity of the medium itself. In neither case is there any more electricity in, or near, the body than before the charge was given to it; for if two bodies, say flannel and rubber, are rubbed together, there is a flow of electricity from the rubber to the flannel, and at the same time there is a displacement or movement of the electricity in the air in the opposite direction, i.e., from the flannel toward the rubber; and this movement in the air is just enough to balance the transference of electricity from the rubber to the flannel.

42. Charging a Body Produces a Strain in the Medium.—Charging a body does not, therefore, consist in increasing or diminishing the total amount of electricity in a body, but rather in distorting the medium about the body; producing a strained condition, from which the medium is always striving to return.

43. Mechanical Analogy.—We may form a mechanical analogy to this process by conceiving the air turned to jelly, in which there are various cavities, channels, etc., filled with water. The jelly corresponds to air and other non-conductors, while the cavities filled with water correspond electrically to metals, the earth, or other conductors. The illustration (Fig. 18) corresponds to a ball charged by a machine, one pole of which was connected to the ground. If water is pumped from a pool of water into a cavity in the jelly which is already filled with water, the cavity will expand, and the jelly will be pressed everywhere back from A as shown by the dotted lines, and will be moved toward the pool from which the water was drawn; the whole volume of water and of jelly being precisely the same as at first. The whole displacement from A toward the pool will be the same as the flow

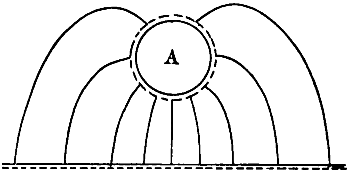

FIG. 18.

from the pool to *A*, and the jelly will be displaced along the curved lines as drawn.

Of course, too, the elasticity of the jelly makes it ready to spring back along these lines as soon as a tube is open from *A* to the pool, along which the excess of water may flow. In a precisely analogous way an electrical machine charges an insulated ball by "pumping" the medium from the ground (to which the other end of the machine must be connected) to the insulated globe. The ground loses as much electricity as the globe gains, and the medium is at the same time displaced from the globe toward the ground. The properties of the charged body are due to the effort of the strained medium to spring back. Of course the displacement from *A* toward the pool will not be along any one line, but will be distributed over a considerable volume: this is what Faraday meant when he said that the lines of force spread out laterally, repelling each other.

44. Distribution of Strain in some Special Cases.—To make these ideas more plain and to see how to apply them, let us take up some special cases and see exactly what takes place.

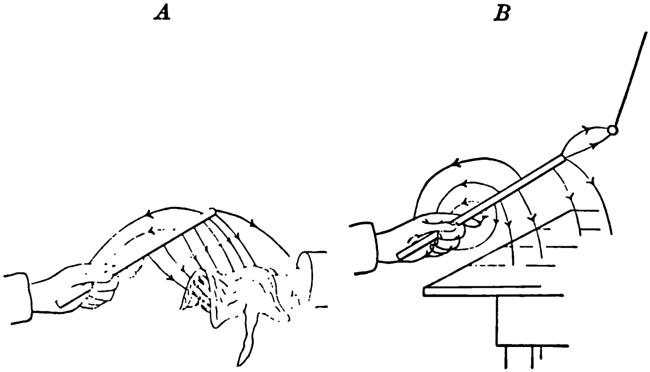

Fig. 19.

charge will always be just equal to the charge on the ball inside of the can.

(3) A similar explanation applies to the electrophorus. The figures show the arrangement of the lines of force with the cover in different positions. Here we meet a new phenomenon, viz., the spark which passes when the finger is presented to the cover. This spark proves that when the strain in the medium is too great, the rigidity of the medium is overcome—there is a sudden slip of electricity along some line; the medium is not bent, but is broken* so that it no longer strives to spring back to its former position. Just so you may blow into a toy balloon, and it yields, but tries to collapse; if you blow too hard, a hole is made and the air rushes out and the balloon collapses. In the case of electricity, however, the break is immediately repaired again, so that the body may be charged as before, as if the edges of the balloon were to immediately stick together again.

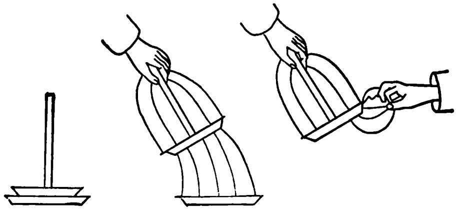

FIG. 21.

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* This weakness and breaking down of the medium seems to be connected in some way with the air or other matter present. We have no evidence that it will break down in a vacuum. No one has succeeded in making a spark pass through a very good vacuum, and there is good reason for thinking it impossible.

CHAPTER IV.

LAWS OF ATTRACTION AND REPULSION—POTENTIAL.

45. Coulomb's Experiments.—To Coulomb * we owe the series of experiments which first established the laws of electric attraction.

The apparatus which he employed in these experiments is called the "torsion balance," because it measures electrical forces by balancing them against the torsion of a fine wire (see Fig. 22).

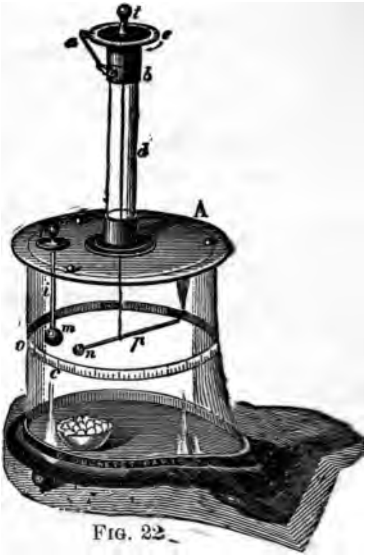

FIG. 22.

A thin bar of shellac *p* is hung by a very fine wire in a glass case. The wire is attached at the top to a knob *t* by which it can be twisted and the amount of twist measured on a graduated circle *e*. On one end of the shellac bar is a pith ball *n*, and another pith ball *m* is supported on a shellac stem *i*, so as to just touch the ball *n*. If a charge is given to the ball *m* and it is then put in place, it will touch *n*, and the charge will divide equally between the two balls (if they are of the same size); *n* will therefore be repelled, and may be brought to any position by twisting the wire at the top.

Coulomb found that if a twist of 90° were re

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* Mémoires Rel. à la Physique, vol. I. p. 107.

order to bring the balls within two inches of each other, a twist of 4 × 90° = 360° would be required to bring them within an inch, and 9 × 90° = 810° would bring them within $\frac{2}{3}$ of an inch; that is, if the distance be $\frac{1}{2}$ the original, the force will be 2^2 times as great, and if the distance be $\frac{1}{3}$, the force will be 3^2 times as great as the original force. This is expressed in words by saying that the force is inversely as the square of the distance.

Again, if the ball *m* is taken out and discharged, then if the balls are of the same size, $\frac{1}{2}$ the charge will be lost; if the ball is replaced as at first, the charge will divide and each ball will have $\frac{1}{2}$ its original charge. On repeating the experiment with this reduced charge, the force at each distance proves to be just $\frac{1}{4}$ as great as in the first experiment. Hence we infer that the force depends on the product of the charges of the balls (since $\frac{1}{2} \times \frac{1}{2} = \frac{1}{4}$).

46. The Law of the Force between Electrified Bodies.—Combining these results, we say that the force between any two charged bodies varies directly as the product of the charges and inversely as the squares of their distances; or in mathematical form, if q and q' are the respective charges on the balls, and r is their distance apart, the force, f, between them is expressed by the relation

$$f \propto \frac{qq'}{r^2}.$$

Of course I have given only a few of the simplest cases: the law was found to hold for a large variety of combinations.

47. Definition of Unit Charge.—In the system described in the first chapter the dyne is the unit of force, and the centimeter is the unit of length. Defining the unit charge in accordance with these units, it is

That charge which, placed one centimeter from an equal charge, attracts it with a force of one dyne. And by adopting this definition we no longer need the sign of variation, but may write more definitely

$$f = \frac{qq'}{r^2}.$$

48. Exact Proof of the Law of Force.—The measurements of Coulomb were made with much care, but the imperfections of the method and the difficulties in manipulation prevented any very high degree of accuracy. Less direct experiments have shown that the law of inverse squares is remarkably exact, if indeed there be any departure from it. The experimental basis for the law is found simply in the fact that in a spherical shell all the charge resides on the surface, while inside the surface there is no flow and no tendency to flow. From these facts the law follows, thus:

Consider any point inside the surface, as *a*, Fig. 23. Through *a* draw many planes, cutting the whole sphere into many pyramids, each having *a* for its vertex. These pyramids will all be double, i.e., for every solid *abcd* there will be another solid, *aefg*; and the bases of these solids will be proportional to the squares of the edges of the pyramids, provided the pyramids are very small. For if the bases were at right angles to the edges, the pyramids would be similar and the law would of course be true; but the base of the oblique pyramid is found by dividing the area of the base of the right pyramid by the cosine of the angle which this base makes with the oblique base. As this angle is the same for both bases, the ratio of the areas is not changed. They are still proportional to the squares of the edges of the pyramids.

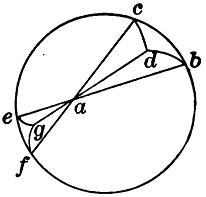

FIG. 23.

Now if there is no tendency for electricity at *a* to flow in one direction rather than another, it is because the force exerted by the charge on the surface *bcd* just balances that exerted by the charge on *efg*. On a spherical surface, the amount of charge per square centimeter is the same for all parts of the sphere. Hence the charge on *bcd* is to that on *efg* as the area *bcd* is to the area *efg*. Hence

$$\frac{\text{charge on } bcd}{\text{charge on } efg} = \frac{\overline{ab}^2}{\overline{ae}^2}.$$

Let X be the whole force exerted at a by each of these charges, and f_1 and f_2 be the forces at a exerted by the charge on unit area of the two surfaces respectively. Then

$$f = \frac{X}{\text{area } bcd} \quad \text{and} \quad f_2 = \frac{X}{\text{area } efg},$$

and
$$f_1 : f_2 = \frac{X}{\text{area } bcd} : \frac{X}{\text{area } efg};$$

hence
$$f_1 : f_2 = \frac{1}{\overline{ab}^2} : \frac{1}{\overline{ae}^2};$$

or the force exerted at a by any charge is inversely as the square of its distance from a.

The demonstration of this proposition was first given by Cavendish, who also made many other important investigations in electricity; but owing to his failure to publish his results, the scientific world was deprived of them until their rediscovery by other investigators.

49. The Leyden Jar.—In 1746, some gentlemen in Leyden conceived the idea that if a charged body were surrounded by glass instead of by air, it would retain its charge better; they therefore undertook to electrify some water in a bottle, leading the charge down to the water by a wire which was to be afterwards removed.

This experiment may be readily repeated by filling a beaker half full of water and holding it in the hand while it is charged by a spoon which stands in the glass and reaches just above the top of the beaker. (Fig. 24.)

FIG. 24.

FIG. 25.

The glass must be thoroughly clean and dry, and filled without wetting the sides. If charged from one knob of the Holtz machine, the other knob should be connected to the ground. The spoon may be charged from the electrophorus, but it will take a good many sparks.

The spoon should be removed by the other hand; but do not drop the glass.

The result of this experiment was a very great surprise to Mr. Cuneus, who first tried it, and hardly less so to those who afterwards repeated it. We can scarcely credit the strange and ludicrous stories told of its violent effects in causing convulsions, bleeding of the nose, loss of strength, etc., to which results the fright or imagination of the experimenters must have contributed.

In the experiment just performed it was necessary to hold the glass in the hand. This is not necessary if the glass is coated on the outside with tin-foil. Instead of putting the water into the glass, a lining of tin-foil is put on the inside. The modern Leyden jar is, then, a glass jar coated on the inside and outside with tin-foil (Fig. 25). Through a hole in the stopper passes a brass rod with a ball on top, and a chain on the bottom to make connection with the inside coating. When a charge is given to the inside, an equal opposite charge is induced on the outside, provided the outside is connected to the ground or to the other pole of the machine. The charge which the jar is thus capable of receiving is many times greater than either coating alone would receive. If the outside coating is insulated, the jar will take but a small charge.

50. What is the Limit to the Charge on any Body?— To understand why the Leyden jar is capable of receiving a greater charge than a sheet of tin-foil of the same size, we must consider why there is any limit to the charge that a conductor will receive.

If the electrophorus cover is charged and touched to a small insulated brass ball, a minute spark passes, charging the ball, but leaving the cover about as strongly charged as before. Repeating the process will not add appreciably to the charge of the ball. If the cover is touched to a large insulated body (e.g. the tin cup on the cake of paraffin), it loses a considerable portion of its charge; and if the cover is again charged and brought up to the cup, another spark will pass, and the process may be repeated several times. It is evident that a greater quantity has been given to the tin cup than to the brass ball. The cup therefore has the greater "capacity." This does not mean that there is any limit to the charge that either body can receive: if a stronger machine were used, both the cup and the ball would receive a stronger charge. Let an analogy explain the matter. Suppose that we had two elastic rubber bags; a certain pump is used to force water into them and can force four quarts into one and one quart into the smaller. Another stronger pump can force six quarts into the larger and one and one-half quarts into the smaller. The relative capacity is the same whichever pump is used to fill them, but the actual capacity in quarts cannot be stated unless we first agree upon some definite pressure that is to be used in filling them. Indeed there is no limit to the capacity of either, except that the bag will finally burst and the water rush out. So in the case of electric capacity: with a sufficiently strong machine, the medium may be more and more displaced till the air finally breaks down and a spark passes, discharging the body; though in this case as soon as the medium is relieved by the discharge, the break is mended and the body may again be charged as before.

When a pump is attached to the rubber bag by a tube, the water in the tube moves toward the bag if the pressure in the pump is greater than that in the bag. As soon as the pressure in the bag is as great as that in the pump, the flow will stop. So with the charged ball: as soon as the electrical pressure on the ball is as great as that on the machine, no further flow will take place and no greater charge can be given.

51. Electrical Potential and Water-pressure.—How can we measure the pressure of electricity?

When water flows into the bag because of the force exerted by the pump, work is done, and as the pressure increases the work required is also increased. Accordingly there are two ways of expressing the pressure: first, in pounds per square inch; second, as requiring a certain amount of work for each cubic inch forced into the bag.

In measuring water-pressure it is more convenient to use the first method, and it is always expressed in this way; but in electrical measurements it is much more convenient to use the second, i.e., to state the work required to carry a unit charge from the earth to the charged body. Suppose, then, that a pith ball has upon it a unit charge. When it is far from any charged body there is but a slight strain in the medium—the pith ball is repelled but feebly by the charge. As it comes nearer, the strain in the medium, and consequently the repelling force, is greater. To bring the charged pith ball to any particular point requires a definite amount of work.

52. Definition of Potential of a Point.—The potential of a point is equal to the work required to bring a unit charge to that point from a great distance.*

53. Definition of Potential of a Body.—The potential of a body is equal to the work required to bring a unit charge to that body from a great distance.

From the first definition it is evident that the difference of potential of two points A and B is equal to the work required to carry a unit charge from A to B.

54. The Nature of Electrical Potential.—It will be plain as we proceed that "potential" is simply another name for electrical pressure, and we shall have frequent occasion to compare it to water-pressure. A few remarks may be added here showing the nature and value of the idea of potential or electrical pressure.

(1) If it takes work to carry a charge from one point to another, this can only be because there is some force to be overcome. On a conductor, if there were such a force tending to move the charge from one part to another, the charge would move in obedience to the force. Hence if the charge upon a conductor is at rest, it is because there is no such force. If, therefore, the charge upon a conductor is at rest, all parts of that conductor are at the same potential.

A surface which has the same potential at every point is called an "equipotential surface."

(2) The same thing is true not only of the surface of the conductor, but also throughout its whole substance. Hence,

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* When the distance is considerable, the force required is very small, and consequently the work done is very small. Strictly speaking, the distance should be infinite, but the result is the same if the distance is so great that the force is inappreciable.

The inside of a conductor is at the same potential as the surface.

(3) The difference of potential of different places is very important, while their absolute potential is of little importance; hence it is convenient to consider the potential of the earth to be zero, and any body connected to the earth is also considered to be at zero potential.

(4) The potential of a body depends not only on the strain in the medium at the surface of the body (i.e., its charge), but as well on the strain all along the path from the body to the earth; thus, the strain at the end of a long conductor is much greater than near the middle, but, on the other hand, it falls off more rapidly at the ends, so that on the whole it requires just as much work to bring the unit charge up to the middle as to the ends.

(5) If a body has a negative charge, a positive charge will, of course, be drawn toward it. Therefore the work done in bringing a positive charge to a negatively charged body is negative, and the potential of the body is said to be negative.

(6) If there are both positive and negative charges near a point, the potential of the point may be positive, negative, or zero, according to circumstances. A body with a negative charge may be at a positive potential because of the presence of some positive charge in the vicinity. Similarly, a body connected with the ground is always at zero potential, but it may have induced charges of either kind. When a positive charge is brought up to an insulated uncharged conductor, both positive and negative charges appear on the conductor, but its potential is positive.

The electrophorus affords a good illustration of these points. When the cover is first placed in position, it has a zero charge and a negative potential; when it is touched, its charge is positive and its potential is zero; when it is then raised, its charge and potential are both positive.

55. Calculation of the Potential at any Point.—We will now calculate the potential at a point due to the charge at any other point. Suppose a charge of q units to be at a point A. We will first calculate the work required to carry a

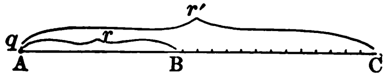

FIG. 26.

unit charge from C to B, where B and C are any two points in line with A and distant r and r' from it. The work is the product of the force on the unit charge by the distance that the charge moves in the line of the force (see p. 9).

The force exerted by q upon the unit charge at C is $\frac{q}{r'^2}$ and at B is $\frac{q}{r^2}$; but as the force is different at each point between B and C, we must divide the distance BC into many small parts, multiply the force for each by its length to find the work done in that space, and then add all these products together. The science of adding such quantities when the quantities are infinitely small and infinitely numerous is called Integral Calculus; but we may readily apply the principles of the calculus to the present problem.

Let there be n dividing points placed between B and C, all equally distant. Call their distances from A, $r_1 r_2 r_3 \ldots r_n$. The force on the unit charge at B due to the charge at A is $\frac{q}{r^2}$, and at the distance r_1 is $\frac{q}{r}$. For the first short distance $(r_1 - r)$ we will assume, as a matter of convenience, that the work done is the product of the distance by the geometrical mean of these forces, or $\frac{q}{rr_1}(r_1 - r)$. The work done in the next space is $\frac{q}{r_1 r_2}(r_2 - r_1)$. Thus the whole work done in passing from C to B is

$$q\left(\frac{r_1 - r}{rr_1} + \frac{r_2 - r_1}{r_1 r_2} + \ldots \frac{r' - r_n}{r_n r'}\right).$$

In adding these together notice that

$$\frac{r_1 - r}{rr_1} = \frac{1}{r} - \frac{1}{r_1}, \text{ etc.}$$

hence the whole work is

$$q\left(\frac{1}{r} - \frac{1}{r_1} + \frac{1}{r_1} - \frac{1}{r_2} + \ldots \frac{1}{r_n} - \frac{1}{r'}\right).$$

Adding the terms within the parenthesis, all the distances disappear except r and r', and the whole work done in going from C to B is $q\left(\frac{1}{r} - \frac{1}{r'}\right)$.

In this proof we assumed that the geometrical mean of the forces could be taken as the average force for each short distance, but nothing was said as to the number of spaces. By infinitely increasing the number of spaces, thus decreasing their length, this assumption is more and more nearly true, but as the expression does not change when we increase the number of divisions it must be that it is exactly right already; therefore,

The difference of potential of two points in line with a charge q is $q\left(\frac{1}{r} - \frac{1}{r'}\right)$.

But it is easy to see that the same law holds true if the points are not in line with the charged body, as follows:

With A as a center draw a circle through C. There is no force along CC', and therefore no work will be done in carrying the unit charge along the arc. The arc is an equipotential line. Hence the same work will be done in carrying it from C to B as from C' to B, and we need not therefore take the points B and C in the same line with A.

The difference of potential of any two points distant r and r' from a charge q is $q\left(\frac{1}{r} - \frac{1}{r'}\right)$.

It may also be noticed that it takes the same work to go along any other path $C'DB$ as along $C'CB$, for whenever the length of the path is increased by going along an oblique path, the force is decreased in precisely the same proportion. Of course if this were not so, there would be no such thing as a potential of the point B, for the potential would be different according to the path travelled in going from the earth to the point.

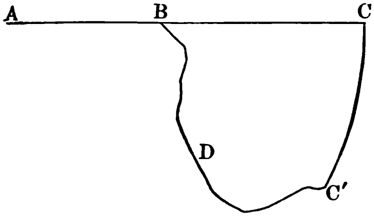

FIG. 27.

This expression gives the difference of potential between any two points; to find the potential of the point B we must suppose the point C to be removed to an infinite distance. Then $\frac{1}{r'} = 0$, and the potential of B is $\frac{q}{r}$.

56. The Unit of Potential.—The unit of potential is the potential of a point one centimeter distant from a unit charge; for in this case $\frac{q}{r} = 1$.

If, as is always the case, the charge is not at a point, but is distributed over different parts of a body, we must find the potential at B due to the charge q at A, and add that due to the charge q' at A', etc., and the whole potential of the point B will be $\frac{q}{r} + \frac{q'}{r'} + \frac{q''}{r''}$, etc. When the charges are distributed over conductors it is necessary to add an infinite number of infinitely small quantities of this sort, and this is impossible in all but a few simple cases. I will take up two or three of the simplest and most useful.

57. The Potential of a Charged Sphere.—The potential of a charged sphere may be found, bearing in mind remark (2), p. 48, that the potential at the surface is the same as at the center. At the center of a sphere, if the radius is R and the charge is q, the potential is $\frac{q}{R}$, because each part of the charge q is at a distance R from the center. Hence $\frac{q}{R}$ is the potential of a sphere of radius R.

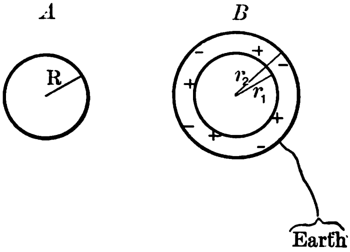

Fig. 28.

58. Potential of Two Concentric Spheres.—Suppose two spheres to be placed concentric with each other, the space between containing only air. Then if the inner sphere is charged and the outer one is connected to the ground, the outer one will have an induced charge just equal and opposite to that on the inner. Let the charge on the inner (radius $= r_1$) be q, then that on the outer (radius $= r_2$) will be $-q$. The potential at the center of the spheres is $\frac{q}{r_1}$, due to the charge on the inner, and $-\frac{q}{r_2}$, due to that on the outer; and the potential at the centre (and at any point inside the inner sphere) due to both charges is $\frac{q}{r_1} - \frac{q}{r_2}$ or $q\left(\frac{1}{r_1} - \frac{1}{r_2}\right)$.

CHAPTER V.

CAPACITY—SPECIFIC INDUCTIVE CAPACITY.

59. Electrical Capacity.—We have already seen that a conductor may be given an indefinite charge, and we now see that the potential is increased just in proportion to the charge.

Definition.—The capacity of a body is equal to the charge which it has when its potential is one.

60. The Capacity of Charged Spheres.—Let us call the potential of any body V, then we may find its capacity by writing $V = 1$ in the expression for its charge and finding the corresponding value of q. For a sphere we found $V = \frac{q}{R}$, and if we now put $V = 1$, we have $q = R$. Hence the capacity of a sphere is equal to its radius.

In the same way, the potential of the inner of two concentric spheres is $V = q\left(\frac{1}{r_1} - \frac{1}{r_2}\right)$, and $V = 1$ gives $\frac{1}{q} = \frac{1}{r_1} - \frac{1}{r_2}$, or $q = \frac{r_1 r_2}{r_2 - r_1}$. This, therefore, is the capacity of the inner sphere. It is worth noticing that the capacity of the spheres is greater in proportion as the distance between them decreases.

61. Capacity of Two Parallel Planes.—If we make a sphere indefinitely large it becomes as flat as may be desired; hence we may use these results to find the capacity of parallel planes.

The capacity of the inner sphere is $\frac{r_1 r_2}{r_2 - r_1}$, and its whole area is $4\pi r_1^2$, hence its capacity per square centimeter is $\frac{1}{4\pi r_1}\frac{r_2}{r_2 - r_1}$, or $\frac{r_2}{4\pi r_1}\frac{1}{d}$, where d is the distance apart of the spheres. Now if both spheres increase indefinitely, their distance apart remaining equal to d, r_1 and r_2 approach the same value, and the whole expression approaches $\frac{1}{4\pi d}$. Therefore $\frac{1}{4\pi d}$ is the capacity per square centimeter of a plane which is near another plane connected to the ground. The formula applies only to those parts of the plane which are not near the edge, as it was assumed in the proof that the planes were infinitely large.

62. Capacity of the Leyden Jar.—It is now evident why the Leyden jar may be given a much greater charge than a tin can of the same size. Suppose a positive charge to be given to the knob. It produces a positive potential in the coating, but if the outer coating be connected to the ground it will have a negative charge induced upon it, and the presence of this negative charge reduces the potential of the outer coating. The thinner the glass the nearer is the outer coating to the inner and the more it reduces its potential, so that the charge may be quite large while the resulting potential is but small. Hence the capacity of the jar is large.

It is equally correct to say that when the machine repels a positive charge from one pole, along the wire to the knob of the jar, the positive on the jar repels it back, but the negative on the outside coating attracts it toward the jar, so that the machine can give the jar a much larger charge than it could if the negative charge were absent.

If the jar is placed on a block of paraffin so that there is no more negative than positive on the outer coating, the jar will take only a small charge. In order to charge it fully, the outer coating must be connected to the ground or to the other pole of the machine.

63. Capacity on the Jelly Theory.—It will be well to go back now to the analogy of a jelly, and see what these results mean. As on p. 37, we will assume that the air is electrically a jelly, while conductors, including the earth, are cavities in this jelly filled with water. Whenever water (electricity) is withdrawn from one cavity, its walls contract (negative charge), while the cavity into which the water is pumped expands (positive charge). There is no limit to the amount of water (charge) that any cavity will hold, if the pump (electrical machine) has unlimited power, but the pressure (potential) must be increased just in proportion to the amount of water forced in. The size of the cavity is measured, not by the whole amount that it contains, which is ambiguous, but by the amount that can be forced in by a pump that produces a pressure of one pound to the square inch.

In this illustration, do not think that an exact identity exists between the two; the analogy is doubtless very crude. It is very possible that there are two fluids concerned in electrical phenomena, and that whenever one is added the other is removed. Still the illustration will assist the mind provided it is not too closely adhered to.

64. How the Capacity of Bodies may be Modified.—We can also understand by the analogy how the capacity or potential of a conductor may be affected by the presence of another conductor.

If water is pumped into a disk-shaped cavity (Fig. 29, *A*) the jelly will everywhere be pressed back; but if a second similar cavity (Fig. 29, *B*) is brought near the first, and is connected by a tube (wire) with the sea (earth), the jelly is now very easily displaced toward this cavity, and the pressure in the first is lowered, or its capacity is increased. The Leyden jar admirably illustrates the same point. The layers of tin-foil are equivalent to two cylindrical cavities with the incompressible jelly outside, inside, and between

(Fig. 30). Now if one tries to force water into the inner cavity, while the outer one is disconnected from the sea or other cavities (insulated), the whole jelly outside of the inner cavity must be pressed outward. No ordinary pressure, therefore, will avail to force in much water; but if the outer cavity is connected by a tube to the sea, it will take comparatively little pressure to force in a large amount. Also the capacity will be greater the thinner the jelly between the cavities. Just so the capacity of two concentric spheres was found to be greater as the jelly was thinner. (Cap. $= \frac{r_1 r_2}{r_2 - r_1}$, see p. 54.)

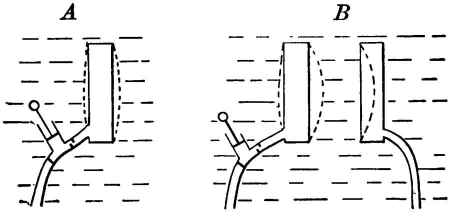

FIG. 29.

65. Specific Inductive Capacity.—In these calculations and discussions it has been assumed that the space around the charged bodies was filled with air. An experiment of Faraday's, already described (p. 32), shows that the amount of induction depends on the nature of the substance through which it acts. Faraday was not satisfied with noticing that there was such a difference, he extended his experiments to determine its amount. The apparatus which he employed * for this purpose consisted of two concentric spheres (Fig. 31). The outer shell is in halves, and the upper half can be lifted off to allow the interior to be reached. The inner ball has a handle by which it may be insulated from the outer shell; while a wire running through this handle allows

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* Exp. Res., vol. I. p. 371, etc.

the ball to be charged while the shell is in its place surrounding the ball. In using the apparatus, the inner ball is charged or discharged while the shell is connected to the ground.

Faraday used two of these "condensers." Let one of them be charged and tested by the torsion balance (Fig. 22). This will show by its deflection the potential of the sphere. If the knob of the charged condenser is now touched to that of the uncharged, and the two are in every respect alike, the charge will divide evenly between the two, and on testing by the torsion balance the potential will be found to be half as great as before. If, however, the second condenser has sulphur or shellac between the spheres, it will take more than half the charge, and the torsion balance shows how much less than half the original potential remains to the first condenser.

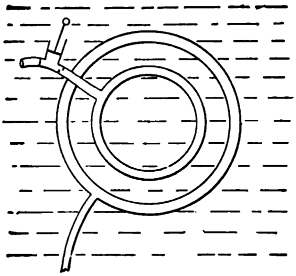

FIG. 30.

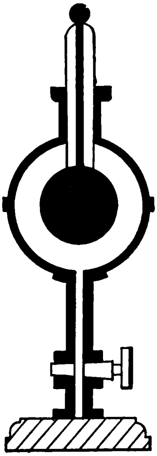

FIG. 31.—FARADAY'S SPHERICAL CONDENSER.

The two condensers are now at the same potential (being connected together), but the one filled with sulphur has the greater charge and therefore the greater capacity. Because the inductive action of the inner globe on the outer is thus increased, Faraday named this property of sulphur, shellac, and other substances, their Specific Inductive Capacity.

Definition.—The specific inductive capacity of any substance is the ratio of the capacity of a condenser when filled with this substance to that which it would have if filled with air.

66. Faraday's Results.—Faraday found the ratio of the capacities for the following substances to be:

Sulphur	2.24
Shellac	2 +
Flint glass	1.76

Faraday's experiments were published in 1837; about the year 1773 Cavendish had made more extensive experiments and by better methods, even using a globe hung in the middle of a room as a standard of capacity. But, as before stated, his researches did little to advance human knowledge, on account of his failure to publish his work.

67. Cavendish's Method of Comparing Capacities.—The following method of comparing capacities is due to Cavendish, and may be easily tried:

Paste two disks of tin-foil on the opposite sides of a sheet of glass, so that they shall be just opposite to each other. There will also be required two metal disks on insulating supports which can be brought very near together or separated to any distance. They should slide in such a way as to be always parallel.

Connect the tin-foil disks to the metal plates (Fig. 32, *A*) and charge them by the electrophorus. Now reverse the connections (Fig. 32, *B*). (The wires must be handled by thin hard-rubber rods.) If the charge on the plates is the same as that on the tin-foil disks, both will now be completely discharged. Touch each wire to the gold-leaf electroscope and see if this is the case. If not, the distance of the plates must be altered and the experiment repeated, till the discharge on reversing the connections is complete.

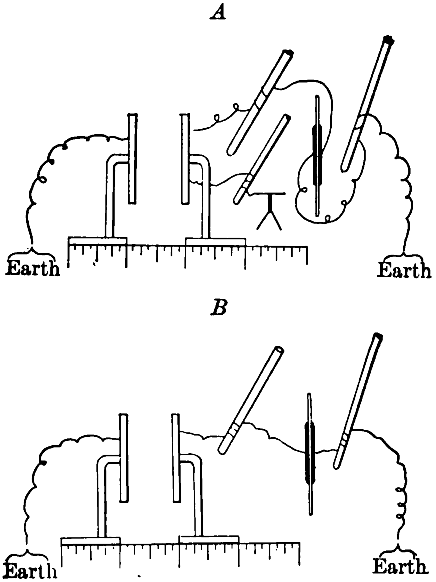

FIG. 32.—DIAGRAM TO SHOW CONNECTION FOR CAPACITY MEASUREMENT.

The capacity of the plates is now the same as that of the tin-foil disks.

Calculate the capacity of the plates from the formula on p. 55. This is also, according to the experiment, the capacity of the tin disks. Calculate the capacity which they would have if separated by air. The ratio of their capacity to that which they would have if separated by air will be roughly equal to the specific inductive capacity of the glass.

68. Criticism of the Experiment. — There are three sources of error in this experiment: first, the formula is only roughly correct for the plates here used; second, the apparatus is not very sensitive; but, third, glass and most other substances have a curious property of viscosity.

If a rod of glass is bent by a weight, the rod will bend more and more as the weight continues to pull. If the weight is removed, the rod springs partly back, but will then continue to go slowly back for several days.

Also if a thermometer is heated, both the mercury and the glass tube expand, but the mercury expands more than the glass and rises in the tube. When the thermometer is cooled again, the mercury and bulb both contract, but the glass is viscous and remains too large and for several weeks the mercury will stand too low, gradually returning to its proper place.

There is a very similar electrical viscosity. When the tin-foil disk is charged, the glass or something in it is strained. If connected to some source of constant potential, the medium gradually yields more and more; the tin takes a larger and larger charge. Then when the disks are discharged the medium does not spring completely back, but returns gradually, so that presently another charge (a "residual" charge) may be taken from the disks. This residual charge is very noticeable with Leyden jars, and one needs to look out for it when handling them.

This electrical viscosity is commonly called absorption (as though the charge "soaked in," which is not the case). It very much interferes with the accuracy of experiments on capacity, and to avoid it experiments have been devised in which the plates are charged and discharged very rapidly, sometimes as many as 6000 times a second.

69. Values of Specific Inductive Capacity.—The following values are among the best yet found for the specific inductive capacities of different solids:

Glass[*]	6.6 to 9.9
Paraffin[*]	2.29
Ebonite[†]	3.15
Sulphur[†]	3.84

Faraday's efforts to find a difference in the specific inductive capacity of different gases were unsuccessful; but later experimenters have observed slight differences, as follows:

Air	1.0000	Hydrogen	0.9998
Vacuum	0.9985	Coal-gas	1.0004
Carbonic dioxide	1.0008	Sulphuric dioxide	1.0037

70. Specific Inductive Capacity of Conductors. — The methods here described are only of use in case the medium is a non-conductor. For liquids which (like water) are fair conductors, other methods may be employed.

Silow[‡] and Rosa[§] have determined the attraction between charged bodies which were suspended in liquids; Quincke[‖] has determined the tension along the lines of attraction and the pressure at right angles to this direction. Some liquids have very high specific inductive capacities. Thus Rosa finds the following values:

Petroleum oil	2.26
Sperm oil	3.09
Turpentine	2.43
Alcohol	25.7
Water	75.7

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[*] Phil. Trans., vol. 172 (1881), p. 372.

[†] Wein. Ber. 66, 67 (1872–3).

Excellent discussions of these and other results and the methods of experiment are to be found in Gray's Absolute Measurements in Electricity and Magnetism, vol. I. chap. 7.

[‡] Pogg. Ann. 156 (1875), p. 389.

[§] Phil. Mag., 5th Ser., vol. 31 (1891), p. 188; 1891.

[‖] Wied. Ann. 19 (1883). See also Gray's Absolute Measurements, vol. I. chap. 7.

71. The Medium has not always the Same Elasticity.— The specific inductive capacity is the measure of the readiness with which inductive action takes place through the substance, i.e., of the amount of displacement or yielding in the substance as compared with air. These experiments show that the medium is most yielding in dense substances, and least so in rare. It has the greatest rigidity in a vacuum, and even in air has its rigidity somewhat reduced. In glass it is not over one-sixth as stiff as in a vacuum.

CHAPTER VI.

ELECTROSTATIC MEASUREMENTS—ELECTROMETERS.

72. Measurement.—Most of the experiments thus far described have been qualitative rather than quantitative; that is, they have been for the purpose of finding what happened under certain circumstances, rather than to measure how much of any effect was produced.

Natural laws are always definite in their action, not only in regard to the general effect produced, but also in the exact amount of the result. Therefore we cannot state natural laws completely without stating just the amount of action in each case.

Maxwell says*: " Those whose curiosity is satisfied with observing what happens have occasionally done service by directing the attention of others to the phenomena they have seen; but it is to those who endeavor to find out how much there is of anything that we owe all the great advances in our knowledge."

73. The Quantities to be Measured.—The important quantities with which we have dealt up to this point are: Charge (or quantity of electricity); Potential; Capacity; Specific Inductive Capacity.

The measurement of specific inductive capacity has already been described. See p. 59.

Since the charge of any body is equal to the product of its capacity and its potential, the first three quantities are

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* Theory of Heat, p. 75.

so related that if we know any two of them we may calculate the third.

74. Measurement of Capacity.—The capacity of certain bodies may be calculated; thus we have calculated it for the sphere, for two concentric spheres, and for two parallel plates. It has been calculated for ellipsoids, cylinders, and a few other figures. For bodies of other forms it can be found only by experimental comparison with bodies of known capacity, as was done, for instance, on p. 57.

75. Measurement of Charge—Electrometers.—The only way in which the presence of a charge upon a body can be recognized, so long as it remains at rest, is by the attraction or repulsion which it exerts upon neighboring bodies Upon this property therefore are based all electroscopes (instruments for detecting the presence of a charge) and electrometers (instruments for measuring the amount of the charge).

Coulomb's electrometer is the best of the early instruments for accurate measurements, and many important investigations have been made by its means, but its use is so difficult and the results so unsatisfactory that it has been entirely abandoned for more modern instruments. In this department, as in many others, we are much indebted to the skill and ingenuity of Lord Kelvin, whose apparatus is unexcelled in all departments to which his attention has been given.

76. Kelvin's Electrometers.—He has constructed two distinct kinds of electrometers; one for detecting and comparing feeble charges, where sensibility is the prime requisite; the other for comparing the force of electrical attraction with the force of gravity, thus allowing strong charges to be compared and at the same time measuring electrical forces directly in dynes.

77. The Quadrant Electrometer.—The first of these instruments is known as the quadrant electrometer, and is shown in Fig. 33. In the interior of this is a flat brass box like a pill-box with its cover, divided into four parts or quadrants (see Fig. 34 *A*). The quadrants diagonally opposite are joined together by wires, *a* to *c* and *b* to *d*. Within the quadrants hangs a thin flat piece of aluminium (the "needle"), shaped as shown in Fig. 34*A*. This needle is kept constantly charged to the same potential by a small machine like the Holtz machine inside the case (called the replenisher).

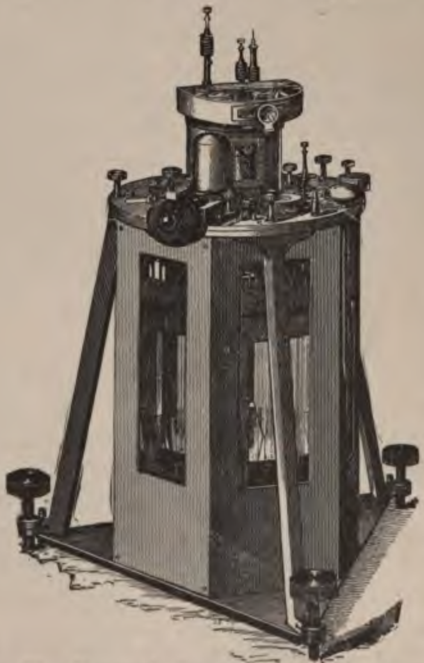

FIG. 33.—KELVIN'S QUADRANT ELECTROMETER.

Suppose the needle to have a positive charge. Then if a negative charge were given to one pair of quadrants, and a positive charge to the other pair, the needle would turn toward the pair charged negatively, and away from the positive pair. If the needle were hung by a silk fibre so as to be perfectly free to turn, the slightest charge would be

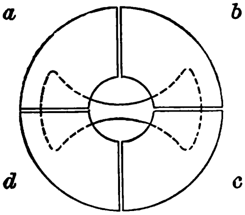

FIG. 34*A*.

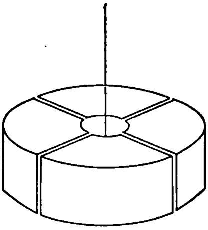

FIG. 34*B*.

sufficient to carry it round until it came entirely inside the negatively charged quadrants, i.e., through an angle of 45° from the position which it occupies in the figure.

To prevent this the needle is hung by two fine silk fibres which are slightly separated from each other (a "bifilar suspension"), and these of course tend to bring it back to its original position. The needle therefore takes up an intermediate position, turning through a greater or less

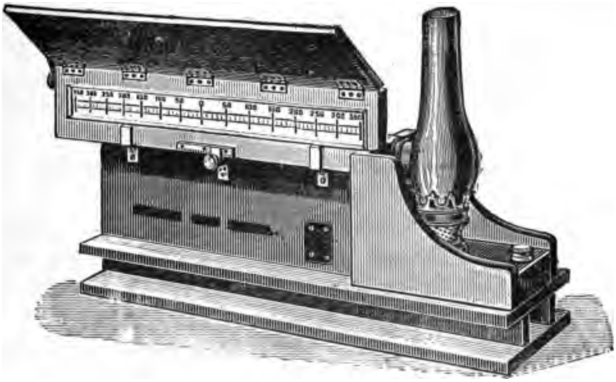

FIG. 35.

angle according to the greater or less potential of the quadrants.

In order to exactly measure the slightest motion of the needle, a very light concave mirror is attached to the wire by which the needle is hung; a pencil of light from a lamp shines through a slit and falls upon this mirror and is reflected by it upon a cardboard scale placed about a yard in front of the instrument, forming there an image of the slit (Fig. 35). This pencil of light acts like a long pointer without weight, but from the laws of reflection it turns through twice as great an angle as the needle itself. A movement of the needle through 1° will carry the spot of light through 35 mm. upon the scale, and motions too small to be otherwise seen are measured with accuracy.*

The delicacy of the quadrant electrometer is such that it will readily measure potentials $\frac{1}{400000}$ strong enough to produce a spark $\frac{1}{16}$ of an inch long.

78. The Absolute Electrometer.—On p. 42 a unit charge was defined as that charge which, placed one centimeter from an equal charge, attracts it with a force of one dyne. The earth attracts one cubic centimeter of water (one gramme) with a force varying in different latitudes from 978 to 983 dynes, but at any place on the earth the exact amount of the force at that place can be measured with great accuracy.

In order, therefore, to measure the charge on a flat plate, Kelvin employs a sort of spring-balance to measure the attraction of the charge for another similar charge and thus compare this attraction with the force of gravity.

The idea of a flat plate hung from one arm of a balance for "weighing" the force of attraction is not new. In 1746 Mr. Ellicott read a letter to the Royal Society describ-

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* This beautiful method for measuring small angles was invented by Poggendorff in 1826, and has come into universal use for all work where small angles need to be accurately measured.

ing such an apparatus.* The principle can be easily illustrated as follows:

Hang a flat plate horizontally below one of the pans of a balance. Beneath this and parallel with it support the cover of the electrophorus by its insulating handle. Counterpoise the plate by weights in the opposite pan of the balance. Now if the electrophorus cover is charged, an additional weight must be placed in the pan to balance the electrical attraction. The electrophorus cover induces a charge nearly equal to its own in the suspended plate, and the attractive force is therefore nearly proportional to the square of the charge.

One principal difficulty with this arrangement is from the irregularity of the force near the edges of the plate. This is avoided in Kelvin's form of electrometer by surrounding the attracted disk by a broad ring (the " guard-ring ") as shown in Fig. 36, so that only the central part of the whole plate is weighed; and for this part the distribution is uniform and the capacity may be calculated from the formula found on p. 54.

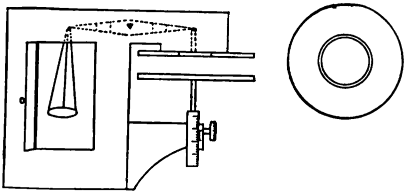

FIG. 36.—SKETCH OF ROWLAND'S FORM OF ABSOLUTE ELECTROMETER.

79. Kelvin's Absolute Electrometer.—Kelvin's Absolute Electrometer, then, consists of a lower attracting disk, carried on an insulating glass stem, and capable of motion in a vertical direction; above this disk and exactly parallel

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* Phil. Trans., vol. 44, p. 96. Priestley's History of Electricity, p. 129.

with it a second disk of which the central part is hung from a delicate spring or the arm of a balance. A hair in the focus of a lens shows when the suspended part is exactly in the plane of the fixed part of the plate. A vernier or micrometer screw measures the distance between the two plates when the electrical attraction just balances the force of the spring (or the weight in the pan of the balance). The whole is covered with a metal shield to protect it from inductive action and to keep off air-currents.

80. Electrostatic Voltmeters.—In addition to these electrometers there are a number of similar instruments based upon the principle of attraction, and called from their use electrostatic voltmeters. Further reference to some of these is made on p. 162.

81. Electrometers Measure Potential.—It will be noticed that these electrometers do not measure the charge upon the bodies to which they are connected, but their own charge. But this depends only on the potential of the charged body, and they therefore serve to measure this potential. The charge upon any conductor can be determined only by finding its capacity and potential, and calculating its charge by the equation

$$\text{Charge} = \text{capacity} \times \text{potential}.$$

Of course it is not these quantities, but the numbers representing the quantities, that are actually multiplied together—as in all other formulæ.

82. Illustrations of Electrostatic Quantities.—To form a general idea of the magnitudes involved in these measurements, the following illustrations are given:

A quart Leyden jar might have a capacity of 400 units, varying with the thickness of the glass.

The difference of potential required to produce a 4-inch spark is about 1000 units.

The Leyden jar above mentioned, if charged to a potential of 70 units (which would suffice for a spark $\frac{1}{4}$ inch long) would contain 28,000 electrostatic units of quantity.

A comparison of these units with those commonly used for electric currents will be found on p. 169.

83. The Nature of Physical Units.—When I refer to a charge of 28,000 units, the question is naturally asked, "What kind of a unit is meant?" In the introduction, p. 7, it was explained how force, work, acceleration, and similar quantities could be measured by a set of units based upon the centimeter, gram, and second (the C. G. S. system). Within recent years, and very largely on account of the labors of Gauss, Weber, Helmholtz, and Lord Kelvin, this system has taken the place of the confusion previously existing, and furnished a most convenient and satisfactory set of units which can be applied to any physical forces now known or to any which may in future be discovered.

All physical forces have this in common, that they produce acceleration or change of motion in the bodies upon which they act. It matters not whether it is the force of attraction of Jupiter for her moons, or the impact of the molecules in the cylinder of a steam-engine, or the repulsion of a pith ball from a charged piece of amber; it matters not whether the cause is plain or whether the force is now observed for the first time and due to unknown causes: still we measure the amount of the force in these units of length, mass, and time.

Since a charge of electricity is measured by the force which it exerts upon a charged body, this charge too may be measured in terms of the same fundamental units.

It is evident that we may go on and measure potential (the work done under certain conditions), capacity (the amount of charge under certain conditions), and any other quantities, electrical or otherwise, by these same fundamental units of length, mass, and time. Therefore when I say that the charge on a Leyden jar is 28,000 units, I mean that if measured in the ways already described, finding its capacity by comparison with a sphere and using the absolute electrometer to determine its potential; then if all measurements of length are made in centimeters, of mass in grams, and of time in seconds, the result will be found to be 28,000.

84. Calculation of the Dimensions of Units.—It is of interest to know in what way the units of length, mass, and time enter in these various units. In the Introduction it was shown that the magnitude of the unit of force in any system is directly proportional to the magnitude of the unit of length, or of mass in that system, and inversely as the square of the unit of time. This was expressed by saying that the unit of force has the dimensions LMT^{-2}.

When two charges of electricity are near each other, the law of their attraction is $f = \frac{qq'}{r^2}$; or if we assume for simplicity that the quantities are equal, $f = \frac{q^2}{r^2}$, and $q^2 = r^2 f$. The dimensions of r^2 are L^2, and those of f are LMT^{-2}, and hence those of q^2 are L^3MT^{-2}, and of q are $L^{\frac{3}{2}}M^{\frac{1}{2}}T^{-1}$.

The capacity of a sphere is numerically equal to its radius, whose dimensions are L. Any other capacity may be found by experimental comparison with the sphere and hence has the same dimensions.

The potential of a charged body is found by dividing its charge by its capacity, and in the same way its dimensions are found by dividing those of quantity by those of capacity; or $L^{\frac{1}{2}}M^{\frac{1}{2}}T^{-1}$.

TABLE OF DIMENSIONS.

Quantity.	Symbol.	Dimensions.
Velocity	v	LT^{-1}
Acceleration..............	a	LT^{-2}
Force.....................	f	LMT^{-2}
Work or energy...........	W	L^2MT^{-2}
Quantity of electricity......	q	$L^{\frac{3}{2}}M^{\frac{1}{2}}T^{-1}$
Capacity..................	C	L
Potential.................	V	$L^{\frac{1}{2}}M^{\frac{1}{2}}T^{-1}$

85. Use of Dimensions.—The knowledge of the dimensions of a quantity is of value in several ways.

1st. All expressions for the same quantity, based upon the same properties, must have the same dimensions, and this is one test of their accuracy. Thus all expressions for area contain length to the second degree, as

$$\begin{aligned} \text{area of a circle} &= \pi r^2; \\ \text{area of a sphere} &= 4\pi r^2; \\ \text{area of an ellipse} &= \pi ab; \end{aligned}$$

and if the area of a new figure were calculated and found to be of different dimensions, the calculation would be shown to be incorrect. In all equations between physical quantities the dimensions of the units entering in the two sides of the equation must be the same; for as houses cannot be equal to apples, so a length cannot be equal to a mass, nor a capacity equal to any quantity of electricity. A test is thus furnished of the accuracy of equations.

2d. We are enabled to compare measurements made in terms of one set of units with those made in terms of another set. Thus to express ten miles an hour in feet and seconds we multiply 10 by 5280, the number of feet in a mile, and divide it by 3600, the number of seconds in an hour, or $\frac{10 \times 5280}{3600} = 14\frac{2}{3}$, because the unit of length appears in the numerator and that of time in the denominator in the dimensions of velocity.

As a second example, suppose we have measured the charge of a Leyden jar in the C. G. S. system and found it to be 50,000 units. Let us find the value of this same charge expressed in inches, pounds, and seconds. To change to inches we must divide by $\left(\frac{\text{length of 1 inch}}{\text{length of 1 cm.}}\right)^{\frac{3}{2}}$ or 4.05, and to convert to pounds we must divide by $\left(\frac{\text{mass of 1 pound}}{\text{mass of 1 gramme}}\right)^{\frac{1}{2}}$ or 21.3. Consequently the charge of the jar is $\frac{50000}{4.05 \times 21.3} = 95.9$, as measured in the inch-pound-second system.

On account of the different standards that have been employed by various experimenters this operation is often necessary in order to compare or make use of the results of the experiments.

86. Dimensions do not show the Real Nature of the Quantity.—It should be noticed that the dimensions of a unit tell nothing as to its real nature, e.g., electrical capacity is not a length although measured in centimeters. A quantity of electricity exerts certain forces under certain conditions and is measured in such a way as to give rise to the set of units just given. Under other conditions it exerts entirely different forces, and when measured by them it leads to an entirely different set of dimensions for the same quantities, forming a new system.

87. The Two Systems.—The system here given is based upon the force of electrostatic attraction, and is therefore known as the electrostatic system. Another system, known as the electromagnetic, will be described on p. 164. Each system is complete in itself, and the dimensions of the same quantity are different in the two simply because based upon different forces exerted under different conditions by the same quantity of electricity.

CHAPTER VII.

MISCELLANEOUS PHENOMENA.

88. Mechanical Force of the Spark.—The tremendous force exhibited by lightning is too evident to require comment. The spark of the Holtz machine will pierce paper or cardboard, and if the spark of the Leyden jar is passed through a card its path is marked by a burr on each side of the cardboard. Leyden jars are frequently pierced by the charges which they contain, and by a suitable arrangement of apparatus thick blocks of glass may be perforated and shattered.

89. Heat of the Spark.—By the discharge of a Leyden jar a thin wire may be heated red-hot, and if the charge is strong enough the wire may be volatilized. The following experiment is due to Franklin:

Lay a narrow strip of gold-leaf on a piece of glass. The strip may be $\frac{1}{16}$ inch wide, and long enough to project beyond the glass at both ends. A similar piece of glass is placed on the first, over the glass strip, and the two are bound firmly together. The discharge from a good-sized Leyden jar is now sent through the strip and the gold disappears. Its place is marked, however, by a purple streak in the glass which is not removed by aqua regia.

Gunpowder may be fired and ether or illuminating-gas may be ignited by the heat of the spark. This property of the spark is frequently utilized for lighting gas in inaccessible places.

90. Appearance of the Spark.—The spark when short is straight, but when long presents a zigzag and forked appearance not unlike a flash of lightning. This appearance is somewhat modified in different gases. When the electrical machine is examined in a dark room and the electrodes are drawn so far apart that no spark can pass, a very different kind of discharge is seen. Upon all knobs and projecting part of the machine which are positively charged there will appear a violet-colored "brush," and a somewhat similar sheet of "glow" on the positive part of the plate as it approaches the diagonal comb. On the negatively charged points and balls there is a bright spot where the discharge into the air is taking place.

91. The Discharge through Vacuum Tubes.—The discharge through a tube from which nearly all the air has been exhausted is very different, and has been made the object of much study. Such tubes ("Geissler's" or "Plücker's" tubes) are often very brilliant when lit up by the discharge of the Holtz machine or Ruhmkorff coil. The color of the glow depends on the nature of the gas, hydrogen having a beautiful rose tint, while oxygen has a much colder and grayer tone.

At certain stages of exhaustion the luminosity of the gas is arranged in peculiar strata, dark and light regions alternating at more or less regular intervals. From the appearances in these tubes, taken in connection with other phenomena, J. J. Thomson concludes* that the passage of electricity through gases is always attended with a breaking up of the molecules of the gas into atoms. From the study of the complicated phenomena shown in these tubes much may yet be learned of the connection between electricity and matter.

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* See the very full discussion of this subject in J. J. Thomson's Recent Researches in Elec. and Mag., chap. II.

92. Crookes' Tubes.—Crookes has experimented much with tubes from which the gases have been removed until there is perhaps $\frac{1}{1000000}$ as much as at atmospheric pressure. In these tubes the most striking phenomena are connected with the negative electrode.

There seems to be a continuous discharge of the atoms of the gas from this electrode, and these travel in a straight line until they strike some obstacle or reach the glass walls of the tube or bulb in which they are confined. Where they strike the glass there is a brilliant phosphorescence excited, whose color depends upon the kind of glass used. If the rays (often called "cathode rays") fall upon a mechanical obstacle, they exert a mechanical force upon it, as may be shown by their turning the vanes of a light mill placed inside the bulb.

Crookes explains these phenomena by assuming that the negative electrode repels the molecules of the gas and thus causes an actual bombardment of the vanes or walls of the tube by molecules which proceed from the electrode, but it is not certain that this is the true explanation.

93. Cathode Rays Pass through Solid Bodies.—The streams have been recently found by Lenard * to pass through a thin layer of glass, metal, etc., even passing out into air at ordinary pressure and producing a phosphorescent effect when allowed to fall on substances placed there. The air itself in this case is made somewhat phosphorescent, and the rays are stopped in less than an inch, while through a vacuum they have been observed to travel more than four feet.

94. Röntgen Rays.—A new and wide-spread interest is now taken in these tubes on account of the remarkable discovery of Röntgen † that radiations from them are able to

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* Translation of Lenard's paper in London Electrician, 1894, March 23 *et seq.*

† London Electrician, Jan. 24 and April 24, 1896.

penetrate bodies opaque to ordinary light, including organic tissues and even the metals. Different substances are opaque to these radiations somewhat in proportion to their density, so that while flesh is quite transparent to them, bones are much less so and the heavier metals are nearly opaque. Since the Röntgen rays do not affect our eyes, their presence is only seen by causing them to fall upon a plate sprinkled with some substance which they will cause to glow with a visible fluorescence, or if they fall upon a photographic plate, they produce an impression which can be developed by the usual methods. The special interest caused by these phenomena is due to the fact that if any part of the body is placed between the Crookes tube and the fluorescent or photographic plate, a shadow is cast upon the plate which is light or dark according to the nature of the substances producing it. Thus a shadow-picture of the hand shows a faint outline of the flesh, a much darker region indicating the bones, while foreign bodies like bullets, needles, etc., produce a still darker shadow. The applications to surgery and pathological study are evident.

Nothing is yet known of the nature of the Röntgen radiations, which are probably very short vibrations, but may be actual streams of matter. The rays originate where the cathode rays strike the walls of the bulb or the anode inside, and travel thence in a straight line. They have not yet been refracted, and but very slightly reflected.

95. A Vacuum is a Non-conductor.—In all these tubes, the discharge seems to depend upon the presence of matter. In tubes from which as much gas as possible has been removed no discharge will pass, the vacuum acting as a good insulator. It seems certain that the conduction observed in what is ordinarily termed a "vacuum" depends upon the presence of the matter still remaining there, and could not take place at all without it.

CHAPTER VIII.

MAGNETISM.

96. Magnetism and Electricity.—The phenomena of magnetism have long been associated with those of electricity, much longer indeed than any true connection has been known. The reason is probably to be found in a general similarity between the two and in the fact that both seem equally mysterious. Thus Young says [*]: " The theory of magnetism bears a very strong resemblance to that of electricity, and it must therefore be placed near it in a system of natural philosophy."

Franklin remarks [†] " As to the magnetism which seems produced by electricity, my real opinion is that these two powers of nature have no affinity with each other."

Yet the progress of the science of electricity has gone on to such a remarkable extent along the line of this connection that it is impossible to go further into the subject of electricity without understanding something of the laws of magnetism. A few simple experiments will be useful.

97. Elementary Facts of Magnetism.—Dip a piece of lodestone into iron-filings. On taking it up it will be found to have the filings adhering in tufts to certain spots.

This property of attraction is not possessed by virtue of any friction, as in the case of electrified bodies, and it is not lost by handling it or by passing it through a flame.

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[*] Young's Nat. Phil., 2d ed., p. 531.

[†] Sparks' Life of Franklin, vol. v. p. 450.

It is a property that can be acquired by only a few substances, certain iron ores, iron, steel, and a few other metals. Any substance having this attracting power is called a Magnet. The spots to which the filings adhere are called Poles.

Now take two knitting-needles. Lay them down and draw the pole of a magnet along each several times in the same direction. (Lift the magnet at the end of each stroke and stroke the needle in one direction only.) The two needles will each have properties like the original magnet. Mark on each needle the end toward which the magnet was drawn. These ends may be expected to have like properties, as they were treated in the same way. Either needle attracts iron-filings at either end; the middle has little or no such power.

98. Attraction and Repulsion.—Suspend one needle by a fine thread in a stirrup of wire or of paper (see Fig. 1) so that the needle shall be horizontal and free to turn. Now hold one end of the second needle toward the suspended one, and one end of the latter will be repelled, while the other end will be attracted. Try the other end of the needle, and it will be found to repel the end which before was attracted, and to attract the end which before was repelled. Similar ends or poles are found to repel, and dissimilar poles to attract.

It will be an excellent plan to refer back to the charged rod (p. 10) and see in what ways the magnet is like a charged rod and in what ways it is unlike. Do not think of the two as in any way the same; any comparison is only by way of analogy, for the magnet is not charged, neither is the electrified rod magnetized.

99. The Needle-points.—The next observation will further emphasize this difference, viz., one end of the suspended needle points toward the north, and the other end toward the south. For this reason the pole pointing toward the north is called the north pole of the needle, while that pointing toward the south is called the south pole.

100. Induced Magnetism.—Hold one pole of a magnet near the end of a bar of soft iron (a horseshoe nail is very good). Dip the other end of the nail into iron-filings and they will be found to adhere to it. Withdraw the magnet and the filings drop off. By presenting the nail to the suspended needle it will be found that the pole of the magnet has induced in the farthest end of the nail a pole like itself, while an opposite pole is found in the nearest end.

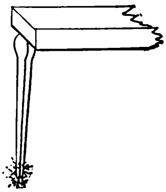

FIG. 37.

The magnet must be very near to the nail, and the effect is much more decided if the magnet actually touches the nail. Even in this case there is no conduction of magnetism from the magnet to the nail. The magnet loses none of its own magnetism, hence the magnetism of the nail is all "induced." No magnetism is ever conducted from one bar to another.

101. Breaking the Magnet.—Much light is thrown on the nature of magnetism by the experiment of breaking the magnet. By means of a strong magnet induce magnetism in a piece of clock-spring. This is easily done, as in case of the knitting-needles, by stroking the spring from one end to the other by one pole of the magnet. One end of the spring becomes a north and the other a south pole. Break the spring in two and test it by the suspended needle to see if all the north polarity is in one end and all the south in the other. Each piece is found to be a complete magnet possessed of two poles and a neutral middle region. Break off both poles of one piece and the remaining middle part will now have two poles, and no matter how small the pieces may be made each will have two poles and will be a complete magnet.

102. Magnetism is not a Fluid.—We find that we cannot cause magnetism to flow from one part of the bar to another part any more than we can conduct it from one bar to another. Each smallest part of a magnet contains the two polarities in equal amounts, and magnetization must consist simply in some peculiar arrangement of these particles in the iron.

103. A Magnet is Polarized.—We may form an idea how this is possible from Fig. 38. If we suppose the magnet to be made up of little particles or "molecules," and each particle to be a magnet, we may imagine that in ordinary iron these particles are not arranged in any definite way, some pointing in one direction and some in others (Fig. 38, *A*). When a magnet is brought near the iron the north poles of the different particles would be made to point more or less in a direction toward the south pole of the magnet, and the end of the bar toward which these north poles pointed would be the north pole of the bar (Fig. 38, *B*).

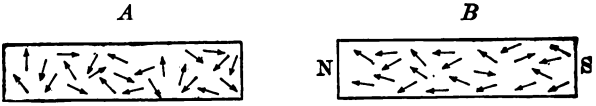

FIG. 38.

An experiment will make it clear how this may be. Cork or seal up one end of a glass tube of ½ inch diameter and 10 inches long. Fill the tube with iron-filings to an inch or two of the top and cork it up. On testing it by the suspended needle, the tube of filings will now be found to act like a bar of iron; i.e., either end of the tube will attract either pole of the needle.

Draw one pole of a large bar magnet several times along the tube and again test it. It will now be found to act like a weak magnet, one end attracting one pole of the needle and the other end repelling the same pole. If the tube is now shaken up it loses this power to act as a magnet and again seems to be a simple bar of iron—not because the magnetized filings have lost their magnetism, but because they are all mixed up and point in all possible directions. Before it is shaken up there are more north poles pointing toward one end and more south poles pointing tôward the other, while in the middle the north and south poles neutralize each other so that it appears not to be magnetic, although the paticles are here magnetized quite as strongly as those near the ends.

Another model will be described on p. 204 which has the advantage that the motions of the separate particles may be seen.

104. Law of Magnetic Force.—When a magnet is placed very close to a tack or small piece of iron, the tack may be seen to move before the magnet touches it; and in testing a magnet by the suspended needle it was still more evident that the magnet exerted a force at a distance, but that the force became much less as the magnet was moved farther off.

Coulomb investigated the law of magnetic attraction and repulsion in the same way that he determined the law of electrostatic force (p. 41), and by the same apparatus; using magnets instead of charged balls. It was his purpose to find the force exerted by one pole upon another pole; and although it is not possible to make a magnet with only one pole, yet, by using long, thin, carefully magnetized bars of steel, he succeeded in removing one pole so far from the other that its influence might be but little felt. One such magnet was hung up at *np* (Fig. 22) by a fine wire, *d*, and then a second magnet was introduced in place of the rod *rm*. The repulsion between the poles *m*, *n*, was then measured by the twist in the wire, and the distance between the poles could be changed by turning the torsion head *t*, from which the wire was hung.

In this way he found that the same law was true for magnetism as for electricity—namely, that the force is directly proportional to the strength of either pole, and inversely as the square of the distance between the poles. Or if m and m' are the strength of the two poles, and r is the distance between them, the force is expressed by the equation

$$F = \frac{mm'}{r^2}.$$

105. Definition of Unit Pole.—We are now able to define a unit pole in the same way that we defined a unit charge of electricity.

A unit pole is one which repels an equal pole at one unit distance with a unit force. (This is true whatever set of units is adopted.)

The C. G. S. unit pole is one which when placed at a distance of one centimeter from an equal pole repels it with the force of one dyne.

106. Magnetic Lines of Force.—While Coulomb's law of force is of theoretical importance, it cannot be readily applied to ordinary cases, because each magnet has two poles which cannot be separated and because the two magnets act inductively upon each other and their strength is mutually affected. Much more useful in ordinary cases is Faraday's conception of Lines of Force. Faraday imagined lines of force starting upon the north poles of all magnets and extending out into the air wherever the magnetic force is felt, and finally terminating upon magnetic south poles. These lines of force must not be confused with the lines of electrostatic force previously described, as they are not at all the same, and the presence of the latter in no way implies that the former are there also.

The lines of force thus imagined have the following properties:

1st. They start upon north poles and end upon south poles.

2d. They constantly tend to shorten like stretched rubber bands.

3d. They repel each other, spreading out as much as their tension permits.

4th. If any substance is present through which they may pass more readily than through air, they will pass through this substance, even going out of their way to do so.

107. Direction of the Lines. First Case.—To better appreciate the meaning of these statements, it will be found very useful to trace out the direction of the lines for a few simple cases.

Lay a piece of magnetized clock-spring, 3 or 4 inches long, on the table, and lay a sheet of paper on it. Sprinkle iron-filings evenly over the paper from a height of one or two feet, and if necessary jar the paper by tapping it lightly. Each filing becomes a magnet and points along a line of force so that the direction of these lines is clearly marked out all around the magnet.

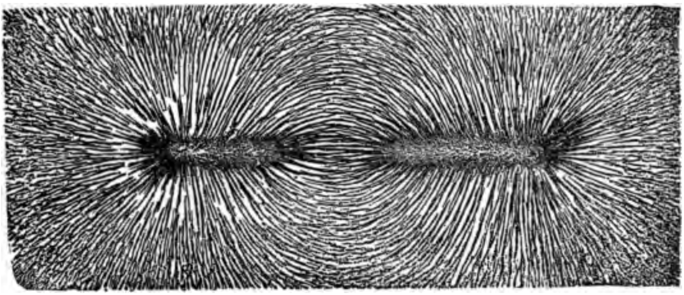

FIG. 39.—LINES OF FORCE. (MAYER.)

There are a number of ways to make these figures permanent. Perhaps the neatest is to use a photographic dry plate in place of the sheet of paper, and hold a lighted match over it after the filings are arranged. On developing the plate the figures are seen.

108. Second Case.—Obtain a similar figure with two magnets lying side by side and having their north poles pointing in the same direction. On comparing this figure with the former, it will be seen that the lines of force repel each other. This repulsion of the lines of force is Faraday's explanation of the repulsion of the magnets when lying in this position.

109. Third Case.—Obtain a third figure, using one magnet and near it a thin bar of iron so placed that it is somewhat oblique to the lines of force at the place. The lines will go out of their course to pass through the iron from one end to the other, as if they preferred this path to any more direct one (magnetic substances are said to be good conductors of lines of force). By examining this figure it will be seen that any tension along the lines of force would act upon the iron bar so that if free to turn it would point along these lines. It is by this tension that the filings are made to point along them.

An examination of Figs. 39 and 41 (or still better, of the filings themselves) will show all the properties here described. Many more figures may be easily made for different combinations of magnets.

If the end of a strip of iron is near one pole of a magnet, e.g., the north pole, the lines of force enter the iron, forming a south pole. Just as many lines emerge from the other end of the iron, forming a north pole, and extend from there to the south pole of the magnet. The iron is drawn toward the nearer pole of the magnet, whichever this may be.

110. Second Method of Drawing the Lines of Force.—Another method of drawing the lines of force near a magnet is much slower, but can be used where the force is much weaker and therefore shows the effect of the earth's magnetism. A sheet of paper is laid on the table, square with the points of the compass, and a piece of magnetized clock-spring is laid on this, pointing east and west. A small compass * is placed near the magnet and a pencil-mark made at both ends of the needle. Slide the compass along till the end of the needle pointing toward the magnet stands over the farther mark, and again mark the position of the farther pole (see Fig. 40). Proceed in this way, sliding the compass a distance equal to its own diameter each time, until the line of force has been traced to the edge of the paper or back to the magnet. In this way the paper is to be covered with lines of dots, which may be connected by a continuous line, and which will show, at each part of the paper, the direction of the magnetic force.

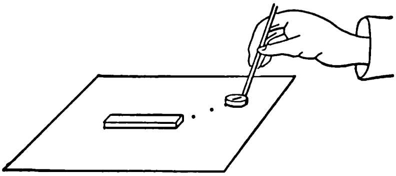

FIG. 40.

This chart shows the combined effect of the magnet and the earth, and shows why the earth's lines of force, by shortening, tend to make the magnet point north and south.

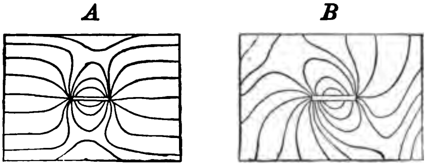

FIG. 41.

Fig. 41, *A* and *B*, shows such magnetic maps with the magnet lying in different directions.

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* A compass with a needle not over one-half inch long is best. If this cannot be obtained, soften a piece of watch-spring and make a punch-mark in it. Harden and magnetize it, and break off one-half inch with the punch-mark in the middle. Balance this on a piece of needle-point which stands up through a thin slice of cork.

111. The Magnetic Field.—Any region where there are lines of magnetic force is called a magnetic field. In a magnetic field, a north magnetic pole tries to move in one direction along the lines of force, the south pole tries to move in the opposite direction. The strength of the field is measured by the force exerted at that place upon a unit magnetic pole; thus a field whose strength or intensity is three units is one in which a unit magnetic pole would be urged by a force of three dynes.

Faraday speaks of the lines of magnetic force as follows*: "It appears to me that these lines may be employed with great advantage to represent the nature, condition, direction, and comparative amount of the magnetic forces; and that in many cases they have, to the physical reasoner at least, a superiority over that method which represents the forces as concentrated in centres of action, such as the poles of magnets or needles."

This idea of lines of force has proved of the greatest value both for convenience in thinking and for purposes of calculation, quite aside from any question as to their actual existence. We shall consider presently the reasons which lead many to suppose that they have such an existence in the medium about magnets.

112. The Number of Lines of Force.—Methods have just been given for finding the direction of these lines at any place. To represent the intensity of the force they are drawn most thickly in those regions where the force is

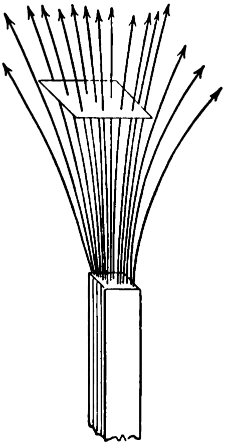

FIG. 42.

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* Exp. Res., vol. III. p. 329.

strongest and are fewer in number where the force is least. If lines are drawn according to this rule, then, on cutting the lines perpendicularly by a plane, the number found passing through one square centimeter of the cutting plane will be the measure of the force. Thus in Fig. 42 a plane of one square centimeter area placed at right angles to the lines of force cuts through eight lines if the strength of the field at that place is eight.

113. Number of Lines of Force Emerging from the Pole of a Magnet.—Adopting this convention, it is easy to calculate the number of lines of force coming from the pole of a magnet. A unit pole is one which produces a unit force at a distance of one centimeter from the pole; i.e., if a sphere is drawn about the pole with a radius of one centimeter, there will be one line of force passing through each square centimeter of the surface of the sphere. Since the surface of the sphere has an area of 4π square centimeters, there are 4π lines of force passing through this surface, and this is the total number of lines emerging from a unit pole. If a pole has the strength m, it produces a force of m units at one centimeter distance, and the whole number of lines emerging from the pole is $4\pi m$.

114. Lifting Power of Magnets.—The number of lines of force going from a magnet furnishes a means of measuring its lifting power. If $\mathcal{H}$ lines emerge from a pole whose area is one square centimeter, and $\mathcal{B}$ is the corresponding number when the armature is brought up to the pole, the attraction between the pole and the armature is

$$F = \frac{\mathcal{B}^2 - \mathcal{H}^2}{8\pi}.$$

F is the load measured in dynes.

If the area is not one, but A square centimeters and $\mathcal{H}$

and $\mathcal{B}$ are the number of lines per square centimeter, then the attraction is *

$$F = \frac{A(\mathcal{B}^2 - \mathcal{H}^2)}{8\pi}.$$

Thus the carrying power of magnets may be calculated from purely electrical measurements without weighing the load.

In steel magnets the value of $\mathcal{B}$ rarely exceeds 10,000, corresponding to a load of 4900 grams per square centimeter, but in electromagnets the value of 40,000 has been reached,† corresponding to a lifting power of 77.8 kilo. (or 171 lbs.) per square centimeter. The electromagnets of dynamo machines have perhaps one-tenth this attracting power.

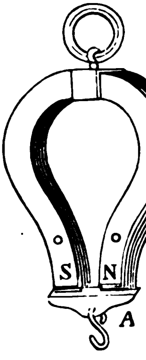

FIG. 43. — HORSESHOE MAGNET MADE OF THIN STRIPS.

115. Permanent Magnets. Coercive Force.—Ordinary magnets are made of steel. Soft iron is more easily magnetized, but unless the bar is very long and slender most of the magnetism disappears when the magnetizing force is removed. Steel bars require a stronger force to magnetize them—their "coercive force" is greater; but they retain a considerable amount when the force is removed, and are not so much weakened by jarring and rough handling as the soft iron.

116. Forms of Magnets.—Magnets are commonly made in the form of a straight bar, or curved in a U shape ("horseshoe" magnets). The horseshoe form has greater lifting power and produces a stronger field than the bar magnet. Thin magnets are stronger in proportion to

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* The proof of this equation is given in Ewing: Magnetic Induction in Iron, p. 247.

† Ewing. Magnetic Induction in Iron, p. 144.

their size than thick, and therefore a common way of making magnets is to build them up of thin strips fastened together. Thus the magnets in the receiver of the Bell telephone are made of four strips of very hard steel, bolted together.

117. Effects of Heat and Jarring.—When magnets are heated or cooled they lose some of their magnetism, and do not recover all of it when they return to their former temperature.

Jarring also weakens them. A wire or thin bar of soft iron will retain a considerable amount of permanent magnetism, but if dropped almost every trace of magnetism instantly disappears.

For these and other reasons magnets gradually lose their strength; and to make permanent magnets that shall retain their strength unchanged requires special precautions.*

Iron and steel lose all their magnetism if heated to a bright red heat, and while hot are not attracted by a magnet.

118. Other Substances are Magnetic.—A few other substances, principally nickel and cobalt, can be magnetized, but not nearly so much as iron. The magnetism of these substances has found very few applications.

119. Diamagnetism.—It had been for some time known, but little appreciated, that bismuth was repelled by a magnet when Faraday undertook his extensive series of experiments † on the magnetic properties of different substances. He found that nearly every substance was either attracted or repelled by a magnet. Bismuth is the most strongly repelled of any substance, but even this metal requires a strong magnet to show the effect. Faraday's experiments not only included the different metals, but wood, water, feathers, paper, and many other substances, organic and

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* For an excellent method of doing this, see the U. S. Geolog. Survey, Bull. 14, p. 171.—Barus.

† Faraday's Exp. Res., vol. III. p. 34, etc.

inorganic, were tried. Most of these were found to be "diamagnetic"; i.e., they are repelled by the magnet. Most gases are also diamagnetic, but oxygen is quite decidedly magnetic.

These substances exert so little force that Faraday was obliged to suspend them between the poles of his powerful electromagnet by a fine thread from a silk cocoon, and to enclose the whole in a glass box to avoid air-currents. When all necessary precautions are taken, a bar of bismuth will stand directly across the lines of force. In this respect as well as in their repulsion by the magnet their behavior is just opposite to that of iron.

CHAPTER IX.

MAGNETIC CONDITION OF THE EARTH.

120. The Earth a Magnet.—Among the first properties of magnets we noticed that when hung up by a thread they point toward the north. This indicates that all about us there are magnetic lines of force extending from south to north. If a map of lines of force were made by the method described on p. 86, with all magnets removed from the neighborhood, the paper would be covered with a series of straight parallel lines.

The earth seems therefore like a great magnet with its north pole near the south pole of the earth, and its south pole near the north pole of the earth.

Like other magnets it can be used to magnetize bars of iron. If a long bar of soft, well-annealed iron is held vertically and struck a sharp blow with a hammer, the upper end will be found to be a south magnetic pole, and the lower end a north pole. If the bar is turned with the other end up and struck, its magnetism will be reversed. A bar of very soft iron may have its magnetism reversed by simply reversing its position.

121. The Compass.—The most important use made of the magnetic properties of the earth is in connection with the compass. It is unnecessary here to point out the importance of this simple instrument for travellers, surveyors, and above all for navigators.*

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* For a very interesting account of the history of the compass, the reader is referred to the Encyc. Brit., 9th edition, vol. VI. p. 225, article "Compass."

122. Magnetic Declination.—The magnetic needle does not point exactly north. The lines of magnetic force instead of going toward the north pole of the earth terminate at a point near the northern part of Hudson's Bay—the "magnetic pole." The angle which the magnetic needle makes with the true north and south line at any place is called the Declination.

123. Inclination or Dip.—The lines of force at most places are not horizontal, but slant downward toward the earth. Thus at Washington they make an angle of 70½° with the horizontal. A magnetic needle which was balanced before being magnetized would, after magnetization, dip down with its north end. For this reason such needles are often provided with a small sliding weight by which they may be adjusted to a horizontal position when carried to places of different "dip."

124. Magnetic Intensity.—In addition to this, the intensity of the earth's magnetic force varies from place to place. Apparatus for measuring this force and changes in its amount was devised by Gauss, Director of the Observatory of Göttingen from 1807 to 1855, and to his untiring labors with those of W. Weber, Professor of Physics in the same place, we owe much of our exact knowledge of the magnetic condition of the earth.

To carry on simultaneous observations in different parts of the world they founded a Magnetic Association, each member of which was to make a series of observations at his own house at certain times, previously agreed upon. By comparing the results of all of these observations Gauss calculated the position of the magnetic poles and constructed a mathematical formula to represent the magnetic force at each part of the globe.

125. Instruments for Magnetic Measurements. — To determine the magnetic declination, an instrument similar to a surveyor's transit is required, provided with a telescope to be turned toward the north star or some object which has been set up just north of the instrument. A magnetic needle on the instrument points to the magnetic north, and the angle between the telescope and magnet is read off on a circle.

Similarly the dip is measured by a magnetic needle turning in a vertical circle and exactly balanced on its centre of gravity. Special precautions are necessary to secure this and other adjustments; even the bending of the needle from its own weight introducing very appreciable difficulties.

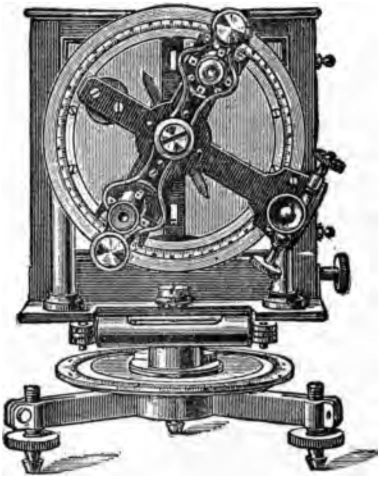

FIG. 44.—DIP NEEDLE. KEW PATTERN.

126. Measurement of the Intensity of the Earth's Magnetic Force.—The measurement of the intensity of the magnetic force is much more complicated, but on account of its importance in the physical laboratory it must be described more fully. The measurement as employed by Gauss is based on the quickness of vibration of a magnetic needle. Whenever a body vibrates, the quickness of the vibration depends upon the force which causes it to move. Thus a stiff spring vibrates more quickly than a flexible one; a tightly stretched cord more rapidly than a slack one. Just so a magnetic needle if suspended by a silk fibre so as to point north and south and set vibrating will vibrate more rapidly where the earth's force is strong than in a place where this force is weak.

It is also true that a strong magnet will vibrate more quickly than a weak one of the same size. Gauss's method of measurement therefore consists of two operations. First the time of vibration of the suspended magnet is determined, then this magnet is used to deflect a small needle which is suspended at some distance. In this way the strength of the magnet is found and the earth's force is measured independently of the strength of the magnet employed.

The measurement as described gives only that part of the magnetic force which acts in a horizontal direction—the "horizontal component." Since the force is really in an oblique line, it is evident that the force as thus found must be divided by the cosine of the angle of dip to give the total force.

An account of the experiment and the theory of the measurement will be found at the end of this chapter.

127. Magnetic Maps.—Maps are constructed to show the values of each of these quantities (Declination, Dip, and Intensity) at the different parts of the earth's surface.

Thus if lines are drawn on the map through all points which have the same declination, they are known as isogonic lines. If lines are drawn through all points having the same dip, these are called isoclinics.

128. Continuous Records.—At several places a continuous record is kept of all these quantities, by means of magnets properly suspended, and provided with mirrors by means of which a spot of light is thrown onto a strip of sensitive photographic paper. The paper is drawn along regularly by clockwork, and as the spot of light moves from side to side a sinuous line is traced which records all variations in the declination, dip, or intensity, as the case may be.

129. Regular Variations.—These records, as well as many experiments, show that all the quantities are subject to continual changes. Thus records of the declination at Paris extend back as far as the year 1540, and have been continued ever since. In Fig. 45 is given a diagram showing by a curved line the observed declination at Paris ever since that time. This line shows that the declination at that place has undergone a regular swing back and forth.

130. Daily Variation.—Of the other regular variations of declination, the daily variation is the most important. The needle points furthest east at about sunrise, and furthest west early in the afternoon. The difference amounts, at Philadelphia, to about 8′. Other variations—the annual, the monthly, etc.—are insignificant in amount.

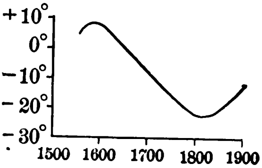

FIG. 45.

131. Irregular Variations. — Besides these regular changes in the position of the needle, there are changes constantly taking place which cannot be predicted or arranged according to any regular law. If a piece of plate-glass mirror is stuck onto a small magnet—a piece of knitting-needle or watch-spring—and the magnet hung by a fibre of unspun silk from some firm support, the needle will never be at rest.* If a small telescope (a spy-glass will answer) is directed toward the mirror and focussed upon the reflection of any object, the image will be constantly moving in one direction or the other—creeping along in a

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* The experiment can be readily tried, but to get rid of accidental motions the mirror must be suspended from a firm support, such as a basement wall, and protected from draughts of air.

strange and unexplained fashion. At times these irregularities are so decided that "magnetic storms" are said to prevail. These very frequently occur in connection with auroral displays and are undoubtedly connected with them. Some connection with sun-spots is also suspected, but the exact relationship is not understood.

NOTE ON THE DETERMINATION OF THE EARTH'S MAGNETIC INTENSITY IN ABSOLUTE MEASURE.

Reference has been made to a method of measuring the earth's magnetic intensity, developed by Gauss, which does not depend upon the strength of the magnet used.

A magnet of length l, whose poles are each of the strength m, has a magnetic moment $\mathfrak{M} = ml$. If the moment of inertia of the magnet is I, and it is set swinging in a magnetic field of intensity $\mathfrak{H}$, its time of complete (to and fro) vibration will be*

$$t = 2\pi\sqrt{\frac{I}{\mathfrak{M}\mathfrak{H}}},$$

and

$$\mathfrak{M}\mathfrak{H} = \frac{4\pi^2 I}{t^2}.$$

The time t is to be observed. I can be calculated from the form of the magnet.

Now let this same magnet be placed in an east and west position with the center of the magnet distant a centimeters from a very small needle, which is so suspended that its angular deviation from the magnetic meridian can be determined. As the poles are of equal strength but opposite sign, the force produced at the center of the needle is

$$F = \frac{m}{(a - l/2)^2} - \frac{m}{(a + l/2)^2}$$
$$= \frac{2mal}{(a^2 - l^2/4)^2}.$$

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* See Lodge's Mechanics, p. 41, where this equation is proved for the compound pendulum.

If $l^2/4$ is so small compared with a^2 that we may neglect it, the equation becomes

$$F = \frac{2ml}{a^3} = \frac{2\mathfrak{M}}{a^3}.$$

Since this force is east and west in its direction, while the earth's force is north and south, the needle will stand along the line of the resultant force, and its inclination to the magnetic meridian will be given by the equation

$$\tan \delta = \frac{F}{\mathfrak{H}} = \frac{2\mathfrak{M}}{a^3\mathfrak{H}},$$

whence

$$\frac{\mathfrak{M}}{\mathfrak{H}} = \frac{a^3 \tan \delta}{2}.$$

a and δ are to be measured. A mirror, telescope and scale are best used for measuring δ.

Having now the value of $\mathfrak{M}\mathfrak{H}$ and $\mathfrak{M}/\mathfrak{H}$, we may divide one by the other to find $\mathfrak{H}$; the magnetic moment of the magnet employed disappears in the result, thus giving an "absolute" measurement of the earth's intensity.

If all measurements have been made using centimeters, grams, and seconds as units, the resulting value will be expressed in C. G. S. units.

We also see how it is possible to measure the magnetic moment, or the strength of the pole, in C. G. S. units. For knowing $\mathfrak{M}\mathfrak{H}$ and $\mathfrak{M}/\mathfrak{H}$, we may multiply them together and determine $\mathfrak{M}$, and having $\mathfrak{M}$ may readily find m. But m is equal to the force which the pole would exert upon a unit pole placed at a distance of one centimeter. Thus we have a perfectly feasible method of measuring the strength of a magnet pole in C. G. S. units.

We shall find that measurements of electric currents are based upon this measurement of $\mathfrak{H}$, so that the experiment here described is the fundamental one in current measurement.

For fuller experimental details, see Stewart & Gee's Practical Physics, vol. II. p. 37.

CHAPTER X.

ELECTRIC CURRENTS—BATTERIES.

132. The Flow of Electricity.—It was explained in Chapter III that when a body is positively charged, the medium near that body is pushed away toward some other body which is negatively charged.

Because of its elasticity this medium is constantly trying to return from the strained condition; therefore if a wire is touched, one end to the positive and the other end to the negative charge, there will be a flow along the wire and the medium will spring back to its original place.

133. Difference of Pressure.—The difference of pressure in the medium (or "charge") is usually produced by rubbing two unlike substances together, but there are many other ways for producing it.

When a card or a piece of mica is quickly split, one piece will be positive and the other negative. When sulphur is melted and again allowed to cool, the crystals formed are strongly electrified. A number of fishes are able to give a shock when touched, and Faraday proved the identity of this electricity with that ordinarily experimented upon in the laboratory.

134. Contact Produces Difference of Pressure. — But while there are many such methods of obtaining charges, they are altogether insignificant compared with that based upon the contact of unlike substances.

When a piece of pure zinc is dipped into dilute sulphuric acid the electrical pressure is different in the acid and the zinc, but no chemical action can be seen to take place.

Pure zinc is not easily obtained. In place of it a strip of ordinary sheet zinc may be placed in the acid until bubbles come freely from every part, then rubbed over with a drop of mercury till the whole surface is covered (too much mercury will make the strip very brittle). Zinc thus amalgamated will act like pure zinc.

If a copper wire is dipped into the acid, the electrical pressure in the copper and the acid is different, but still there is no visible chemical action.

In each case the electrical pressure is higher in the acid than in the metal, but the difference is not the same in the two cases. If we say that the pressure in copper is one lower than in acid, then that in zinc is two lower than in acid; hence the pressure in copper is one higher than in zinc. Therefore if the zinc and copper are touched together, the difference of pressure will at once cause a flow from the copper to the zinc. This allows the medium to return to its natural (unstrained) condition where the zinc and copper touch; but on account of the chemical forces where the metals touch the acid this condition cannot be a permanent one—at least, the chemical forces do their best to upset it by urging a flow from zinc to acid with more force than from copper to acid. The result is a continuous flow from zinc to acid, acid to copper, copper to zinc, constituting what is called an electric current.

It was stated that the acid did not attack the zinc, and this is true at the first, but as soon as the zinc touches the copper and a current starts, chemical action begins, and continues as long as they remain in contact.

135. Copper and Zinc in Acid.—If the experiment be tried, as above described, of placing a strip of amalgamated zinc and a piece of copper wire in dilute sulphuric acid, it will be found that few bubbles appear upon the zinc; but as soon as the copper and zinc touch each other, bubbles rise abundantly from the copper, while the zinc is seen to be dissolved. This remarkable fact will be considered later. The chemical action is attended by a flow of electricity, as will be proved when the effects of the current have been described.

136. The Taste of the Current.—Meanwhile you may notice that if a strip of zinc and a strip of copper are placed, one on the tongue and the other under it, a distinct " coppery " taste will be noticed when the strips are touching each other, which is absent when they do not touch. This taste may easily be identified as the same that is produced when the two wires from a voltaic cell are touched to the tongue.

It is to be noted that while the chemical forces cause the flow from zinc to acid where the acid and zinc touch, the flow from the copper to the zinc is caused by the elasticity of the medium, which has been distorted by the chemical forces and is now trying to fly back into its natural position.

137. The "Jelly" Analogy of the Current.—It will be well now to return to the analogy between electricity and jelly—the air and non-conductors corresponding to the jelly, while conductors are represented by cavities in the jelly filled with water.

The zinc, copper, and acid (conductors) must each correspond to cavities, and to represent the contact of the copper and zinc we will have a tube containing a stop-cock so that the current may be allowed to flow or not. Two men of different strength represent the force of the atoms of acid and zinc, and acid and copper, producing a difference of pressure. Each man is provided with a pump and pumps the water from his cavity (metal) into the connecting tube (acid), so that the pressure in the right cavity is one and that in the left cavity is two below the pressure in the connecting-tube. While the stop-cock at the top is closed, the pumps act only long enough to produce this pressure, and after this is produced there is no further flow of water. If now the stop-cock at the top is opened, the pumps will keep up a continuous flow, the water passing from right to left (copper to zinc); for while the pumps are acting in contrary directions and consequently oppose each other's action, still one pump is stronger than the other and can force the water back through it.

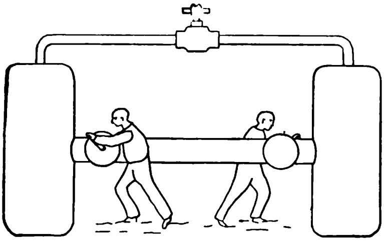

FIG. 46.

138. Galvani and Volta.—The first hint that a current of electricity, such as has been described, could be produced came to an Italian physician, Galvani, who was experimenting on the effect of electricity upon frogs' legs when he discovered that if two connected pieces of metal were touched, one to the nerve and the other to the muscle, the muscle would contract as if an electric discharge were sent through it. The circumstances of the discovery are variously related, and it is not certain whether the discovery was the result of accident or not. Galvani attributed the action to some nervous or vital force of the frog in setting up the current, but it was soon proved by Volta, Professor of Natural Philosophy at Pavia, that a similar current could be produced by the contact of the metals with an acid, as well as with the legs of a frog.

Volta's theory was that the current was produced by an electromotive force at the point where the two metals came in contact. This view is still held by many, though the necessity of chemical action in keeping up the flow is universally recognized. While the question can hardly be settled by direct experiment, yet certain facts seem to me to prove conclusively that the theory already advanced, which places the difference of pressure at the contact of metal and acid, is the correct one. Further reference to these facts will be found on p. 108.

139. The Condensing Electroscope.—Volta invented an extremely sensitive electroscope, by which he succeeded in showing the charge produced by the contact of unlike substances. This consists in a gold-leaf electroscope which terminates above in a large flat plate; a similar plate resting upon the first has an insulating handle attached by which it may be raised without discharging it. Both plates are thinly coated with shellac varnish, so that when one rests upon the other they are still insulated from each other. Lay the upper plate upon the lower. Take in the hand a strip of zinc, to the other end of which a strip of copper has been soldered. Touch the copper end of the strip to the upper plate (at a spot where the varnish has been removed) while the zinc end is held in the hand. Touch the finger of the other hand to the lower plate. Remove first the finger from the lower plate, then the metal strip from the upper plate. By this process, if there is any difference of pressure, there has been a charge given to the upper plate and a corresponding opposite charge to the lower plate by induction. Also the plates are so near together that their capacity is large (see p. 54); and although the difference of

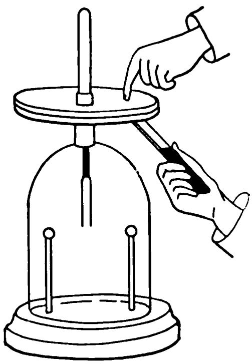

FIG. 47. — VOLTA'S CONDENSING ELECTROSCOPE.

pressure may be but small, the charge is by no means so small. If now the upper plate is raised by its insulating handle, the distance between the plates being greatly increased, their capacity is lessened, and the pressure of the charge is much increased. The charge flows down to the leaves in very perceptible quantity and a plain divergence of the leaves is seen.

This experiment requires a nicely constructed instrument and considerable practice to even show the existence of a charge. By the quadrant electrometer the pressure may not only be shown, but may even be measured with considerable accuracy.

Volta asserted that he found by this experiment a difference of pressure between copper and zinc, but the experiment might equally be claimed to show a difference of pressure between zinc and the hand, as explained above; the moisture of the hand acting as the liquid in the cell.

140. Volta's Contact Laws.—Volta established an important law as to the contact of metals; viz., that when a series of metals touch each other, the difference between the pressure of any two metals in the series is the same as would be produced by these two metals touching directly. Thus, if iron, zinc, tin, lead, are connected together in the order mentioned, the difference of pressure between the iron and the lead is just what would be obtained if the iron itself touched the lead. If, in such a chain, the metals are bent round to form a closed ring, no flow of electricity will take place, because the difference of pressure at one contact is just balanced by that at the other. This "contact law" of Volta does not apply to liquids such as water, acids, and salt solutions, if these are included in the chain; thus we saw that the difference of pressure between copper and acid plus the difference between acid and zinc is not equal to the difference between copper and zinc. It is because of this that a flow is produced in a circuit containing an acid;

while in a circuit composed simply of metals at a uniform temperature no flow takes place when the circuit is closed.

141. Effect of Unequal Heating.—The contact law is not true even for metals if these are not all at the same temperature. Thus if a copper wire and two iron wires are twisted together at the ends (Fig. 48), and one junction is at the temperature of 0° C., while the other is at 200°, then the difference of pressure at the cold junction will be about ten times as great as at the hot. Now if the ends *a* and *b* are brought together, the difference of pressure at the cold contact will overpower that at the hot, and a flow will take place from *b* to *a*, passing from copper to iron at the hot junction.

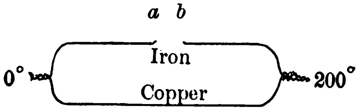

Fig. 48.

The difference of pressure, even in the most favorable cases, is very minute, being, in the case here described, about $\frac{1}{500}$ as great as when using zinc, copper, and acid. While it provides a means of getting electrical energy directly from heat, yet on account of the low pressure obtainable, the method has never proved economical on a commercial scale.

142. Thermoelectric Diagram. — The laws connecting the temperature and the electromotive force for different metals are most simply seen by referring to the diagram Fig. 49. The area of the trapezoid bounded by the two oblique lines, bearing the names of the metals employed, and by the two vertical lines through the numbers which give the temperatures of the junctions, is the electromotive force of the combination. This area is calculated by multiplying the average vertical distance between the oblique lines by the difference in temperature: if the oblique lines cross between the temperatures used, the area on one side of the point of crossing must be considered positive, and on the

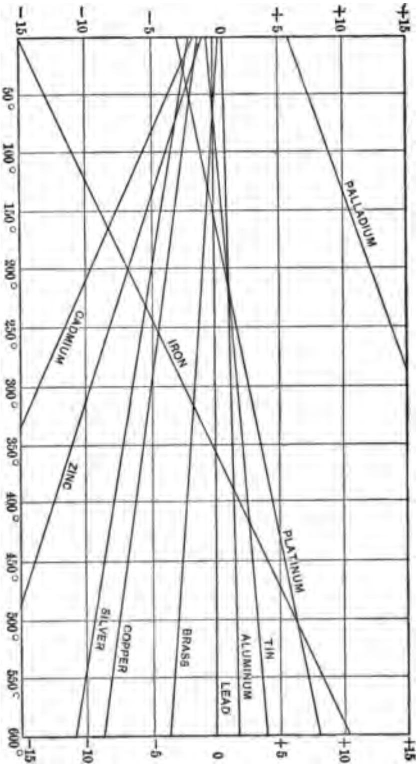

Fig. 49.—Thermoelectric Diagram. (Tait.)

other side negative; they are therefore to be subtracted in finding the total area.

143. Thermopiles.—To increase the pressure produced by heating the junction of two metals, a number of pieces are often connected in a series, the two metals alternating, so that when the alternate contacts are heated and the remaining ones cooled, the effects may be added (see Fig.

50). When so arranged the instrument is known as a thermopile, and may be used to produce currents in the laboratory, which, although feeble, are very steady and are occasionally employed.

A more usual application of the thermopile is for thermometric use. The one set of contacts may be placed against a body whose temperature is sought, when a flow of electricity will take place nearly proportional to the degree of heating. The thermopile has been especially useful in the investigation of the laws of radiant heat.* When the face containing one set of contacts is blackened and exposed to the source of radiation, a current is set up. A modification of this instrument made by Boys, who combined the thermopile and the galvanometer for measuring its current, in one instrument, is capable of showing the heat from a candle at a distance of a quarter of a mile.

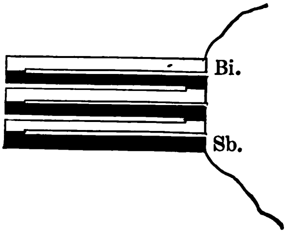

FIG. 50.

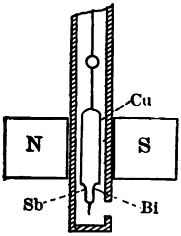

FIG. 51.

144. Peltier Effect. — Since the electrical energy of thermoelectric currents is obtained from the heat applied to the circuit, we must look for a disappearance of heat at some part of the conductor. Peltier discovered that when electricity flows from one metal to another the joint is heated or cooled according to the direction of the current. If a weak current is passed through a thermopile and the

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* See Tyndall's "Contribution to Molecular Physics," or his "Heat as a Mode of Motion," for examples of this use.

terminals of the thermopile are then connected to a suitable galvanometer, a current will flow, showing that one set of junctions has been heated and the other cooled.

While the effect thus observed is very slight, considerable theoretical importance attaches to it. It may readily be seen that the cooling thus produced depends upon the difference of electrical pressure in the two metals at their point of contact. Therefore, since the cooling is very slight, the difference of pressure is also slight, and for the principal difference of pressure in a series consisting of zinc, acid, copper, we must look for the principal difference of pressure at the contact of acid and metal (p. 104); this view is further confirmed by chemical principles which show that the difference of pressure may be determined by the energy with which the substances combine with each other, which is considerable in the case of zinc and acid, but hardly appreciable for zinc and copper.

145. Voltaic Cells.—While, therefore, the difference of pressure produced by the contact of metals is so slight as to be almost wholly of theoretical importance, it is far different with metals and acids. The strips of copper and zinc (p. 101) dipping in dilute acid constitute what is called, in honor of the inventor, the voltaic cell. Such a cell produces a difference of pressure hundreds of times greater than is commonly produced by the contact of unlike metals.

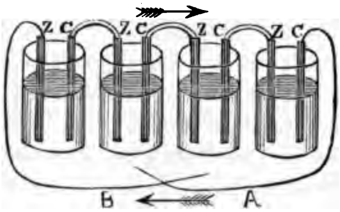

FIG. 52.

Yet even this difference of pressure is small compared with that caused by friction—about $\frac{1}{10000}$ as great as is required to produce a spark one-eighth of an inch long. In order to increase this pressure as much as possible Volta joined a number of such "elements" or "cells" together (Fig. 52).

The pressure in the first copper strip is higher than in the zinc strip. A second copper is attached to the first zinc, and hence is at nearly the same pressure*; but the second copper is as much higher than the second zinc as the first copper is above the first zinc, each cell thus adding its own difference of pressure to that of the preceding. Thus the four cells have a difference of pressure between their terminals four times as great as one cell.

A number of voltaic cells joined together is generally called a "battery." (The word battery is frequently applied in a loose way to a single cell, but this use is incorrect).

146. Electromotive Force.—The difference of pressure between the copper and zinc plates in Volta's combination will cause a current to flow if the plates are connected by a wire. It exerts a force tending to set the electricity in motion and hence is called "electromotive force."

Each kind of cell to be described has its own electromotive force which does not depend at all upon the size of the cell, but only on the materials used. When a greater electromotive force is required, it must be secured by connecting several cells in series as described in the last section.

Other things besides difference of electrical pressure tend to produce a current, and are therefore included under the name "electromotive force"; but in a battery, if we cut the wire joining the zinc and copper plates, we shall find a

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* It will be remembered that two metals when in contact do not come to exactly the same pressure. The difference is so slight as to make no practical difference.

difference of pressure equal to the electromotive force of the battery.

Methods for measuring electromotive force will be given later. For the present it is sufficient to say that it is commonly measured in terms of a unit called the volt (Volta). See also Chapters XI and XV.

147. Polarization.—Batteries made with zinc, acid, and copper as here described are rarely used at present on account of their inefficiency. Their great defect is that as soon as the current flows, hydrogen is liberated in small bubbles over the copper plate. This has two bad effects: first, it gets in the way of the current and, being a bad conductor, weakens the current by causing a resistance to its flow; second, freshly liberated ("nascent") hydrogen is itself a very active substance chemically, and the copper is thus plated with a substance nearly as active as the zinc. Now the difference in pressure between the copper and the zinc is due to the difference of their chemical activity toward the acid; therefore this difference of pressure is much lessened when the copper becomes coated with the nascent hydrogen.

This action is known as "polarization" of the battery. Since the value of a cell for most purposes depends upon its constancy and its low resistance to the current, quite as much as upon a high difference of pressure between its poles, these early cells were very defective in providing no means for disposing of the hydrogen.

148. Constant Cells. Daniell's Cell.—The earliest of the constant cells, and one of the most constant, is Daniell's. Like most of the constant cells, it has two liquids (Fig. 53) which are kept from mixing by a cup of unglazed porcelain, which becomes soaked with the liquid, and hence allows the current of electricity to flow readily through it. A hollow cylinder of zinc is placed in a glass jar; inside this is the porous cup and a strip of copper in this cup. The outer jar is filled with dilute sulphuric acid. In the porous cup is a saturated solution of copper sulphate together with crystals of the salt, which will be dissolved as the solution becomes weakened by the electrical action.

The action of the cell is as follows: The sulphuric acid attacks the zinc, as in Volta's cell, but the hydrogen which is thereby released attacks the copper sulphate and replaces the copper in this salt. Therefore copper and not hydrogen is deposited on the copper pole, thereby causing little or no polarization. The substances used up are, therefore, zinc and copper sulphate, and the chemical products are zinc sulphate and copper.

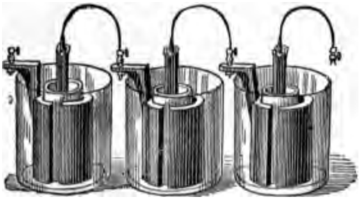

FIG. 53.—A TWO-FLUID BATTERY.

149. Amalgamation of the Zinc.—The zinc in these cells and those that follow (except the "gravity") should be amalgamated, as was the strip used in the experiment on p. 100. The unamalgamated zinc, on account of impurities and irregular structure, is at a higher electrical pressure in some spots than in others. Local currents are therefore set up which rapidly consume the zinc without producing any useful effect. Amalgamation prevents this waste.

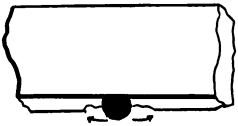

FIG. 54.

150. Gravity Cell.—For telegraph work in this country the gravity battery is almost exclusively employed. In the bottom of a glass jar is placed a copper plate. (Several strips of copper standing on edge are often used.) Then copper sulphate crystals are placed in the bottom to a depth of one or two inches. A zinc casting is hung in the jar near the top, and the whole is filled with water, covering the zinc. When the poles are connected, zinc sulphate is formed by the action of the copper sulphate solution, and copper is deposited on the copper plate. The action is not unlike that of the Daniell's cell, except that as the zinc is in a solution of zinc sulphate instead of sulphuric acid, there is no " local action " or waste of zinc when the current is not flowing, and there is therefore no need of amalgamating the zinc. The porous cup is not used, because the zinc sulphate solution is lighter than the copper sulphate and floats on it—whence the name " gravity battery."

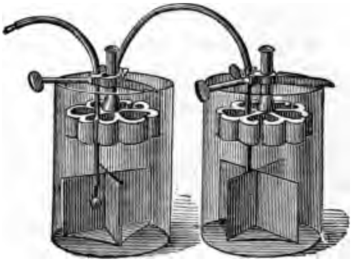

FIG. 55.—GRAVITY CELL.

To maintain the cell, copper sulphate must be added from time to time, and the zinc sulphate solution must be dipped out and replaced by water.

The cell works nicely so long as a current flows, but when standing idle for any length of time the liquids diffuse into each other, and the copper sulphate will reach the zinc and attack it. Copper is then deposited on the zinc and the life of the cell is shortened.

151. Grove's Cell.—Grove's cell is like Daniell's in that it has two liquids kept apart by a porous cup. The zinc is in sulphuric acid, but in place of copper sulphate it employs strong nitric acid, and as this would rapidly dissolve copper, the latter is replaced by a strip of platinum. The hydrogen which would be liberated on the platinum plate in this cell is attacked and oxidized by the nitric acid, forming water. At the same time there are liberated various oxides of nitrogen which are given off as very offensive and injurious gases. Because of the expense of platinum, and still more because these fumes are poisonous and ruin all apparatus which they touch, this cell has passed out of use in this country, being replaced by the bichromate cell.

152. Bichromate Cell.—This cell employs a plate of hard carbon (similar to that used for electric-light carbons) in place of the platinum strip of Grove's cell, and instead of nitric acid, for oxidizing the hydrogen, a solution of bichromate of potash containing a little sulphuric acid. This salt has a great deal of oxygen, and when sulphuric acid is present it very readily gives up the oxygen. In the present case this oxygen attacks the hydrogen, which is thus converted to water. No gaseous fumes are liberated in this process, and hence the battery has not the disadvantages of the Grove. This battery is the one most generally used in the physical laboratories of this country when strong currents are needed and when a dynamo current (and storage battery) is not available.

153. One-fluid Constant Cells.—All the constant cells yet described contain two fluids, and as these fluids are always mixing by diffusion, they require constant care and renewal. The extensive introduction of telephones, electric bells, alarms, etc., has caused a large demand for some battery which will require little attention and yet be ready for use at any moment. Numerous batteries are on the market which meet these requirements, but hardly any of them can maintain a strong current for any length of time. They are therefore known as "open circuit" batteries. Of these the Leclanché may be taken as a type.

154. Leclanché Cell.—The peculiarity of this cell is that the depolarizer is a solid instead of a liquid. The zinc (a simple rod) is placed in a glass jar containing a solution of ammonium chloride (sal ammoniac). The carbon pole is in a porous pot, which is packed with a mixture of black oxide of manganese and broken coke and then sealed up.

In this cell the oxidation of the hydrogen is accomplished by the contents of the porous cup and is but slow, hence a strong current will cause an accumulation of hydrogen bubbles on the carbon pole, causing the cell to polarize. On standing a while it recovers from this condition.

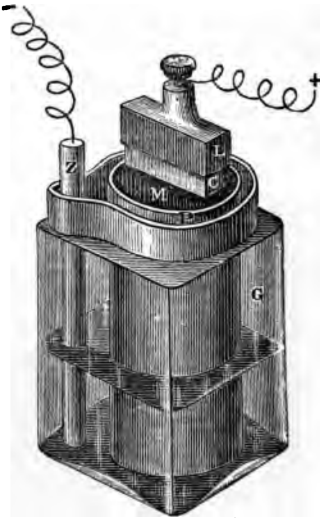

FIG. 56.—LECLANCHÉ CELL.

In some of these cells, the depolarizing mixture is formed into a cake which is held against the carbon pole, and the porous cup is dispensed with. In others the depolarizer is entirely omitted, and the carbon pole is placed directly in the solution.

155. Edison-Lalande Cell.—It will be seen that the special usefulness of the Leclanché cell is due to the employment of a solid substance as depolarizer, whereby there is no diffusion to injure the cell while standing on open circuit. A cell has been introduced in which this feature is retained, but which can be also used for strong continuous currents, having a low resistance and little polarization.

An amalgamated zinc plate is placed in a very strong solution of caustic potash. The positive plate is a compressed cake of copper oxide. The potash does not act upon the zinc while the circuit remains open, but on closing the circuit the zinc is dissolved, forming potassium zincate ($2KOH + Zn = K_2ZnO_2 + 2H$), while the hydrogen as fast as liberated is oxidized by the copper oxide, which is thus reduced to metallic copper.

This cell is convenient for laboratory purposes, because it does not require to be set up every time it is wanted. It has, however, two serious drawbacks. In the first place, the carbonic dioxide of the air would unite with the caustic potash of the solution, forming potassium carbonate, and hence the solution must be covered with a thick layer of paraffin oil to exclude the air. Then the difference of pressure of the positive and negative plates is low, amounting to about $\frac{3}{4}$ that of the Daniell's cell and less than $\frac{1}{2}$ that of the bichromate. The zinc is therefore not used to good advantage, and more cells are often required for the same work.


FIG. 57.—EDISON-LALANDE CELL.

156. There are Numerous Other Cells.—Many other cells have been introduced, and some of them have found extensive application. Descriptions of these will be found in the larger treatises and in special works, such as Park Benjamin's Voltaic Cell.

157. Expense of Batteries.—Nearly all cells which derive their energy from chemical action employ zinc as the metal which is used up. This zinc is used in the battery much more economically than is coal in steam-engines, yet the cost of coal is so much less than that of zinc, and its energy of combination is so much greater, that it costs vastly more to obtain power from batteries than from steam-engines.*

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* The discovery of a simple battery which would employ coal as

158. Storage Cells.—The possibility of employing the steam-engine to produce electric currents has led to the development of a form of battery quite different in its use from those already described. Two or more plates of lead are placed in a jar of weak sulphuric acid: one of the plates is covered with lead peroxide, or more often the plate is punched full of holes which are filled with the peroxide. The other plate is constructed in the same way but the plugs of lead peroxide here have been reduced to the state of spongy lead. When in use the lead plate is oxidized while the peroxide plate is reduced until a lower oxide is formed.

The chief peculiarity of this cell is that, when thus exhausted, the plates are not taken out and replaced, but a current from a dynamo is sent through in the reverse direc-

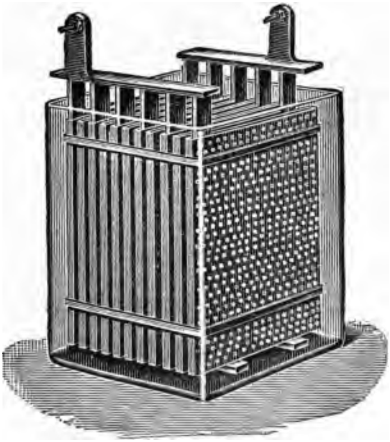

FIG. 58.—STORAGE CELL.

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the negative electrode and oxygen from the air as the oxidizing agent would immediately banish all steam-engines from use and substitute electric motors. The amount of coal consumed would be about $\frac{1}{10}$ as great as in the steam-engine.

tion. This current by its chemical effect (see p. 178) produces changes which restore the cell to its original condition, one plate being reduced to spongy lead, and the other oxidized to the peroxide. They seem to "store up" the current and are hence called storage cells, although there is really no storage of electricity. Other cells may be used as storage cells, for instance the Edison-Lalande.

159. Uses of Storage Cells.—Storage cells are coming into extensive use for supplementing dynamos, enabling these machines to rest altogether during parts of the day when but little demand for lights exists, and assisting the dynamos in the evening during the hours when the demand is heaviest. Extensive experiments have been made with more or less success to use them for street-car work, placing them on the cars, and thus making the trolley unnecessary; but so far their use in this way has been very limited.

160. Electromotive Force of Cells.—The electromotive forces of the different cells are about as follows:

	Volts.		Volts.
Daniell................	1.10	Leclanché...........	1.48
Gravity...............	1.	Edison-Lalande.....	.81
Grove.................	1.94	Storage...............	2.00
Bichromate...........	2.00		

CHAPTER XI.

LAWS OF THE VOLTAIC CURRENT.

161. The Strength of the Current.—Any of the cells just described will produce a difference of electrical pressure and tend to cause a current to flow. The amount of this current will depend upon the electromotive force thus produced, and also upon the resistance which the conductors have. Much confusion and vagueness occur in the descriptions of early writers before the law of the current was clearly stated by G. S. Ohm.*

162. Ohm's Law.—Ohm's Law states that when any electromotive force tends to produce a current in any circuit, the strength of the current is equal to the electromotive force divided by the resistance, or in mathematical form

$$i = \frac{E}{R}.$$

Thus if we introduce a high electromotive force into a circuit without increasing the resistance, we increase the intensity of the current proportionally; while if the electromotive force and resistance are increased in the same proportion the current is not at all affected.

We also see from this law exactly what is meant by "resistance," for

$$R = \frac{E}{i},$$

or the resistance is the ratio between the electromotive force and the current which it produces.

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* Die galvanische Kette mathematisch bearbeitet. 1827.

163. The Flow of Water.—Similarly, when water is forced through a pipe, the flow depends upon the "head" and the resistance of the pipe to the current. On doubling the head, the flow will increase, but it will not be just doubled. In the case of electric currents, however, no experiments have been able to detect the slightest departure from the law as stated by Ohm.

164. Fall of Pressure Along a Tube.— The flow of water through a tube will help us to understand the flow of electricity in a wire. A piece of apparatus arranged to illustrate this is shown in Fig. 59. A small tube *ab* is provided with six upright glass tubes *d, e, f, g, h, j,* A rubber tube *c* connects the end *a* to a faucet and a gentle stream is allowed to flow. As the water is turned on it will rise in the vertical tubes, which will thus act as manometers or pressure-indicators, to show the pressure in different parts of the horizontal tube. In *d* the water stands highest and in *j* lowest, but the difference in pressure between *d* and *e* is the same as between *e* and *f*, etc. The flow in the first section of the tube may be considered as due to the difference of pressure at the points *d* and *e*; and as the flow is the same at all parts of the tube, and as the tube is of uniform bore, the difference of pressure will be the same between *d* and *e* as between *e* and *f*. If, however, an extra resistance be introduced between *f* and *g* (which may be done by having an india-rubber section at this point, which may be compressed by the fingers), the pressure at *f* will immediately rise, while that at *g* will fall. These facts are exactly in accordance with the statement that

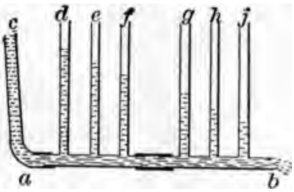

FIG. 59.

$$E = Ri.$$

the difference of pressure E depending simply upon the current flowing and the resistance. The resistance of 60 inches of pipe is of course six times the resistance of 10 inches, and the difference of pressure between the ends is six times as great. Introducing extra resistance at any point requires increased difference of pressure to maintain the flow through this part of the pipe.

165. Fall of Pressure Along a Wire.—In the same way the resistance of a wire is greater in proportion as its length is greater. Along a uniform wire the pressure falls off uniformly, while an increased resistance at any point produces a corresponding increase in the difference of pressure if the strength of the current is to be kept unchanged.

It is plain that a large tube offers less resistance to the flow than a small one, and it is equally true that a large wire offers less resistance to the electric current than a small one.

To sum up, the resistance of a wire is directly proportional to its length; it is inversely proportional to the cross-sectional area of the wire; it also depends upon the material of which the wire is made.

166. Specific Resistance.—In order to construct a chart or table to show the relative resistance of different materials it is desirable to decide upon a wire of standard size and form. When the term "specific resistance" is employed it is understood to mean the resistance between the opposite faces of a block of the material in the form of a cube each edge of which is one centimeter long.

Resistance is expressed in terms of the ohm. The ohm is the resistance of a thread of mercury of one square millimeter cross-section and 106.3 centimeters long, at the temperature of melting ice. This value is taken as representing almost exactly 1,000,000,000 absolute C.G.S. units of resistance, as explained on p. 165.

The resistance of alloys is generally much greater than that of the metals of which they are composed, but their resistance varies less with changes of temperature, making them very convenient for standards. Alloys are now made (manganin and constantan) whose resistance varies hardly at all for ordinary temperatures.

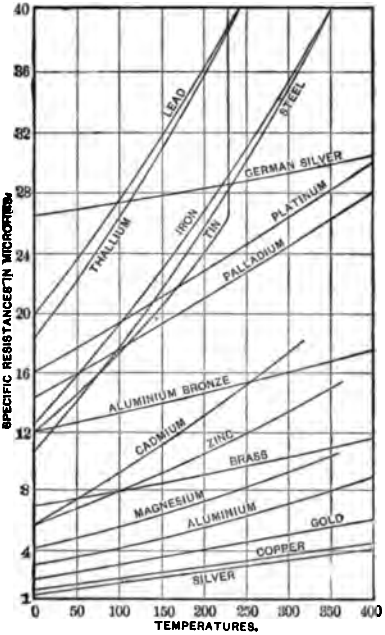

FIG. 60.—CHART SHOWING THE RESISTANCE OF A NUMBER OF METALS AND ALLOYS AT DIFFERENT TEMPERATURES.

167. Currents in Divided Circuits.—When several paths are available for the current, a larger current will flow than if but one path existed; i.e., the resistance of the circuit is less. Ohm's law enables us to calculate the resistance of several wires, whether these are joined so that the current may divide between them, or so that all the current must go through each.

168. Resistance of Wires in Parallel.—Let the wires (resistance R_1, R_2, R_3, etc.) be connected "in parallel" as shown in Fig. 61.

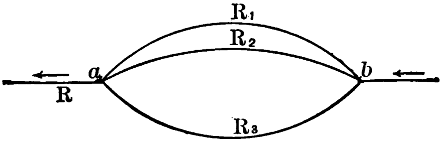

FIG. 61.

Here let the currents in the wires be C_1, C_2, C_3. Call the whole current i and the united resistance R, so that $i = \frac{E}{R}$.

Since Ohm's law applies to each wire, $i_1 = \frac{E}{R_1}$, $i_2 = \frac{E}{R_2}$, $i_3 = \frac{E}{R_3}$; then since $i = i_1 + i_2 + i_3$, $\frac{E}{R} = \frac{E}{R_1} + \frac{E}{R_2} + \frac{E}{R_3}$, and $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$.

Because of this relation, and because it is often of use in calculations, the quantity $\frac{1}{R}$ is called the "conductivity" of the wire; and when several wires are connected in parallel, the conductivity of the whole is the sum of the conductivities of the separate wires.

If $R_1 = R_2 = R_3$, then $R = \frac{1}{3}R$ for three wires; and for any number of wires, n, the resistance is $\frac{1}{n}$ that of one wire.

When wires are connected in this way the current does not choose the easier path to the exclusion of the others, but divides as shown by the law

$$i_1 : i_2 = \frac{1}{R_1} : \frac{1}{R_2},$$

i.e., in proportion to the conductivities of the separate paths.

169. Resistance of Wires in Series.—Now let three wires be connected in "series," as shown in Fig. 62, and

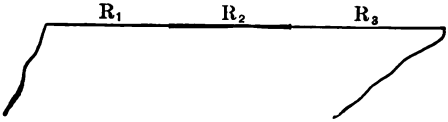

FIG. 62.

let the difference of pressure at the ends of the wires be E_1, E_2, and E_3. The whole difference of pressure is E, and the whole resistance is R. Since Ohm's law applies to each wire and also to the whole series, we have

$$R = \frac{E}{i} \quad \text{and} \quad R = \frac{E_1}{i}, \quad R_2 = \frac{E_2}{i}, \quad R_3 = \frac{E_3}{i}.$$

But $E = E_1 + E_2 + E_3$, and the current is the same in all the wires; $\therefore R = R_1 + R_2 + R_3$.

If several wires are connected in series, the whole resistance is the sum of the resistances of the separate wires.

170. Experimental Proof.—These results may be verified by experiment. Four spools of wire are mounted on a board (Fig. 63), all the wires being of the same length

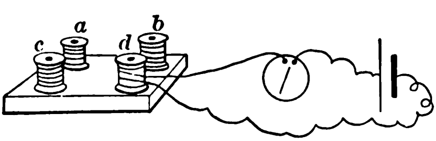

FIG. 63.

(say 25 feet). *a* and *b* contain German-silver wire No. 28, *c* is of the same but No. 24, and *d* is of copper No. 28.

A voltaic cell and a galvanometer,* each of low resistance, can be put in circuit with one or more spools of wire. Measure the strength of the current when *a*, *c*, and *d* are successively placed in the circuit; when *a* and *b* are placed in series, and again in parallel. It will be found that *a* and *b* in series allow but one half the current that passed through *a* alone, while placed in parallel they allow twice the current to pass that was found to flow through *a* alone. The current through *c* is greater than through *a* in proportion as the cross-section of the wire exceeds that of *a* (ascertained by reference to a table or by actual measurement). The current through *d* is much stronger than through *a*, showing the high conducting power of copper compared with that of German silver. These results should be studied and compared with the statements made as to the effect of size and arrangement of wires on the resistance of the circuit.

171. Arrangement of Batteries.—When a number of voltaic cells are to be arranged in a battery the same rules hold good as for wires. Placing two cells in parallel (Fig. 64) produces a battery having the same electromotive force as one cell; but since the two are in parallel, they have but one half the resistance of one cell. This arrangement is to be adopted when the rest of the circuit has but low resistance, so that the resistance of the battery is an important part of the whole resistance.

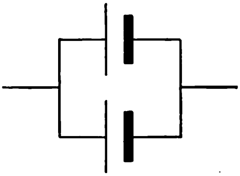

FIG. 64.

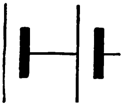

FIG. 65.

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* This galvanometer is described on page 137.

If the two cells are placed in series (Fig. 65), the electromotive force of the battery is twice that of one cell, and its resistance is also double. If there were no other resistance than that of the battery, the current from two cells thus arranged would be no greater than for one alone. This arrangement (in series) is used where the principal part of the resistance is outside the battery, so that the increase of battery resistance is unimportant. The best arrangement therefore depends on the work to be done.

172. Illustration.—To illustrate this let us take the case of two cells each having a resistance of two ohms and an electromotive force of one volt. It is desired to send a current through a wire whose resistance is one ohm. First connect the cells in series, then

$$E = 1 + 1 = 2, \quad R = 2 + 2 + 1 = 5, \quad i = \frac{E}{R} = \frac{2}{5}.$$

Again, let the cells be connected in parallel, then $E = 1$; the resistance of the two cells is one half that of one cell, or one ohm, and $i = \frac{1}{1+1} = \frac{1}{2}$, which is rather greater than by the first arrangement. Suppose, however, that the resistance of the wire were 100 ohms, then by the first arrangement we would have $i = \frac{2}{104}$, and by the second $\frac{1}{101}$, and the series arrangement gives nearly twice as strong a current as the parallel.

CHAPTER XII.

MAGNETIC PROPERTIES OF THE CURRENT.

173. Oersted's Discovery.—When Volta devised the electric battery little was known of the properties of the current * and less of its laws: there was no connection known between magnetism and electricity. All scientific study of the current is based upon a momentous discovery made by Oersted in 1820 of a force exerted by the electric current on the magnetic needle.

Let the zinc and copper plates of a voltaic cell be connected by a wire, and turn it so that the wire shall run north and south. Just above the wire hold a small compass, and the needle will be immediately turned toward the east or west (according to the direction of the current). Place the compass just below the wire, and the needle will turn to the other side. Reversing the current in either position reverses the deflection of the needle.

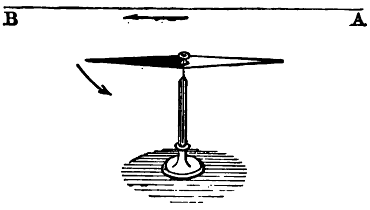

Fig. 66.

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* The electric discharge was known to produce a painful sensation (discovered by the inventors of the Leyden jar in 1746); to heat a fine wire (Kinnersley, about 1765); to decompose water (Nicholson and Carlisle in 1800). Cavendish, about 1775, undertook to compare the electric resistance of salt water and copper wire by the feeling when he took a discharge through one and then through the other.

174. Form of the Lines of Force.—It is thus evident that there are magnetic lines of force near the wire, and that their direction is neither along the wire nor toward the wire. To examine their direction more carefully, arrange the wire, connected with the cell, so that a part of the circuit runs vertically. On the table place a large bar magnet with its north pole pointing exactly north, and close to the vertical wire. Before passing the current through the wire hold a small compass near the wire at such a height that it has no decided tendency to point one way rather than another—the earth's force at this height being nearly neutralized by the magnet.

Now pass a current through the wire, and the needle immediately turns at right angles to the wire. No matter which side of the wire you hold it, the needle is at right angles to the wire, and if the direction of the line of force were now marked out as was done in the neighborhood of the magnet (p. 86), the direction of the line would be circular.

Since the bar magnet does not exactly neutralize the earth's force, the lines are not exact circles, but approach this more or less nearly as the earth's force is more or less completely neutralized. The direction of the lines of force about a vertical wire when the earth's force is not neutralized is shown in Fig. 67.

The direction of the lines of force may also be shown by filings on a card through which the vertical wire passes, but the experiment will require a very strong current.

FIG. 67.—UNIFORM FIELD DISTURBED BY A LINEAR CURRENT.

175. Direction of the Lines of Force.—It is often useful to employ a needle to show which way the current in a wire is flowing. This is readily done by remembering a simple rule. All ordinary screws, bolts, corkscrews, etc., are "right-handed," i.e., a rotation toward the right sends the screw forward. The same relation holds between the direction of the current and the lines of force about it. That is, as the current (flowing from the copper to the zinc) flows along the wire, the lines of force point around the wire in a right-handed direction; i.e., a north pole would try to travel in a right-hand rotation about the wire, as shown in Fig. 68.

176. Peculiarities of the Force.—The force exerted by an electric current upon a magnet is remarkable in many respects. It is due to the motion of the electricity, for electricity at rest exerts no magnetic force (water flowing in a tube exerts no force, due to its motion, on anything outside the tube); again, the force is neither toward the wire nor away from it, but at right angles to its direction, while the force of gravity, electrostatic and magnetic attraction, the forces between the molecules of a gas, etc., are all toward or away from the attracting bodies.

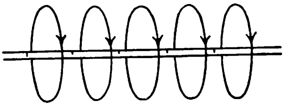

FIG. 68.

177. The Magnet Exerts a Force on the Wire.—Since a current exerts a force on a magnet, it is necessary to suppose that the magnet exerts an equal force upon the conductor carrying the current. This may be readily tested by experiment, using the apparatus known as Ampere's frame.* Pass the current from two or three cells through

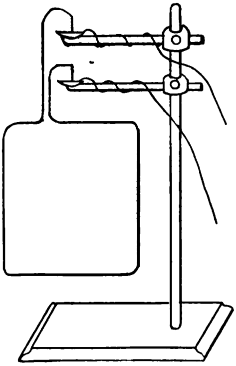

FIG. 69.—A HOME-MADE AMPERE'S FRAME.

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* This may be constructed as follows: Cement a watch-glass to each of two pieces of wood and support these on a retort or filter-stand (Fig. 69). Put mercury into the glasses and let two (insulated) wires from a battery dip into the mercury. A piece of copper wire four feet long has a needle soldered to each end and is then bent into rectangular shape as shown. Both needles should dip into the mer-

the wire and hold near it a horseshoe magnet. The circuit will be drawn in between the poles of the magnet or repelled away from them. Reverse the current, and the attraction or repulsion will be reversed. Bring one pole of a bar magnet near the wire, and the latter will attempt to move across the lines of force.

The nature of the force will be more clearly seen if a bar magnet (wrapped in paper) is placed near a light flexible conductor and a current is then passed through the latter (Fig. 70).

A suitable conductor is formed of six feet of gold thread such as is used for the decoration on military uniforms, or which may be untwisted from tinsel cord.

It will be found that the conductor always endeavors to move at right angles to the lines of force of the magnet. In so doing it wraps itself spirally about the magnet. If the flexible conductor is near a horseshoe magnet, it will be drawn in between its poles. On reversing the current, the conductor is shot out again, in each case moving at right angles to the lines of force.

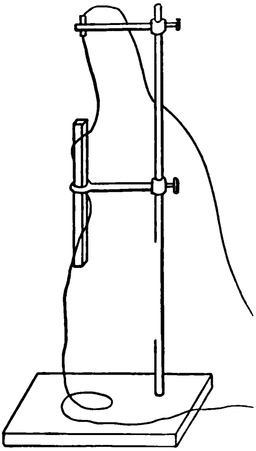

FIG. 70.

178. Biot and Savart. — The first careful study of the laws of the force between magnets and currents was made by Biot and Savart, who measured its intensity by swinging small magnets at different distances from the current, and deduced the following laws.

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cury, but the weight should come on but one. When thus adjusted the frame easily turns when influenced by any force.

179. Laws of the Force.

I. The force is proportional to the length of the wire.

II. It is inversely as the square of the distance from the wire.

To these laws Faraday * added a third.

III. The force is proportional to the quantity of electricity flowing along the wire.

The magnetic property of the current is the one almost universally used in electrical measurements, and these laws are amply confirmed by daily experience.

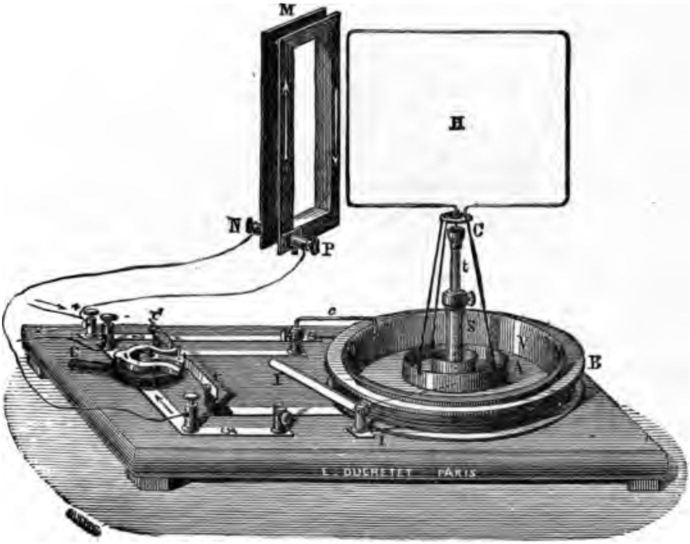

FIG. 71.—AMPERE'S FRAME, ARRANGED TO SHOW THE FORCES BETWEEN PARALLEL CURRENTS.

180. Force between Currents.—Currents exert a force upon magnets; magnets exert a force upon currents. Ampere showed that currents also exert a force upon other

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* Faraday. Exper. Res., vol. I. p. 104.

currents, and by a series of brilliant experiments* determined the laws of this force. To appreciate these forces we may again make use of Ampere's frame. A coil of wire is connected in series with the suspended frame of the apparatus, so that the current flows through both. If the coil is held so that the current in the adjacent sides of the coil and of the suspended frame is in the same direction, that side of the frame will be attracted. If the coil is turned over so that the current in it flows downward while that in the frame flows upward, the two wires will repel each other.

Parallel currents attract each other when in the same direction, and repel when flowing in opposite directions.

181. These Forces Due to Lines of Force.—The conception of lines of magnetic force already introduced will be of assistance here. A few diagrams are given of the field produced by the mutual action of currents or currents and magnets (Fig. 72, *A*, *B*, *C*, *D*), and in each case it will be seen that the force as given by Ampere's rules can be included in the statement that the lines of force repel each other and tend to shorten.

182. Maxwell's Rule.—This shortening draws the currents and magnets together so that "every portion of the circuit is acted on by a force urging it across the lines of magnetic force so as to include a greater number of these lines within the embrace of the circuit."

In Fig. 72, *C*, examination shows that the magnet if drawn into the coil would oppose and therefore lessen the number of the lines of force; in Fig. 72, *D*, on the other hand, the nearer the magnet comes to the middle of the coil, the greater the number of lines. Hence in the former case the force is a repulsion, while in the latter there is an attraction.

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* For a description and discussion of these, see Maxwell's Electricity and Magnetism, Part IV. Chap. II.

Fig. 72, *B*, shows that the coils tend to rotate and then to approach each other.

A little consideration will enable the student to draw approximately correct figures for two vertical currents in which the currents are in the same or in opposite directions and for any other case ordinarily occurring.

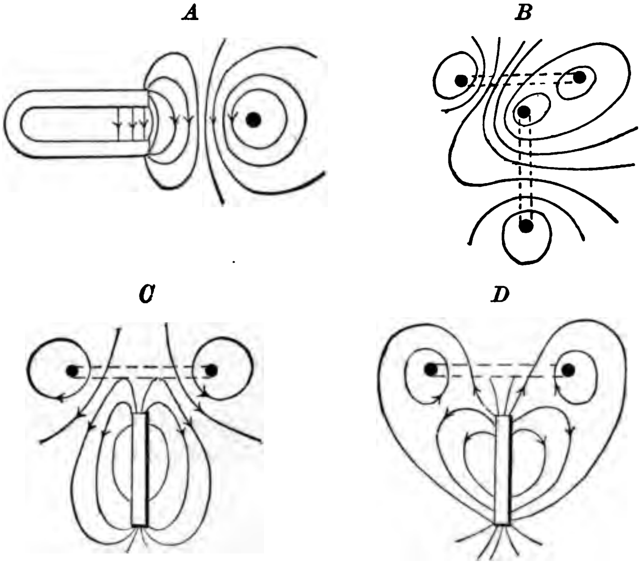

Fig. 72.—Rough Sketch of the Lines of Force in Various Cases

A, A Horseshoe Magnet near a Linear Current.
B, Two Circular Currents.
C and *D*, A Bar Magnet near a Circular Current.

In every case the general direction of the force can be immediately deduced from the two properties of the lines of force, viz., their repulsion and their tendency to shorten.

CHAPTER XIII.

MEASUREMENT OF CURRENTS.

183. Instruments for Measuring Currents.—It has been stated that the ordinary measurement of electric currents is based upon the discovery of Oersted and the subsequent investigations upon the magnetic properties of the current.

The instruments used are called

Galvanometers—if the force is between magnets and currents;

Electrodynamometers—if the force is between currents and currents.

Ammeters are either galvanometers or electrodynamometers so constructed as to be portable and adapted to commercial use by ordinary workmen.

184. Galvanometers.—When a current flows through a coil of wire, lines of force are set up at right angles to the plane of the coil as shown in Fig. 74. If, therefore, a magnetic needle is suspended at the center of this coil by a fibre of silk, it will turn so as to point along the lines of force. Fig. 73 shows a form of galvanometer adapted to measure fairly strong currents. The current enters the coil through the binding-posts at the side. The coil contains a number of turns of wire depending on the strength of the current to be measured. At its center is the needle on a jeweled center turning upon a steel point. A long pointer attached to the needle sweeps over a scale graduated in degrees, by which the deflection of the needle is measured.

185. Method of Use.—To use the galvanometer it is set up with the plane of the coil standing north and south and the circle is then adjusted so that the pointer stands at 0°.

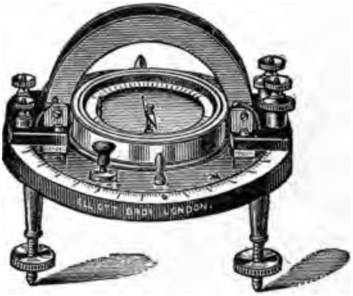

FIG. 73.

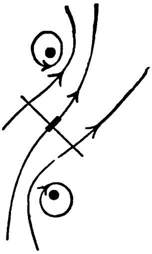

FIG. 74.

FIG. 73.—SMALL TANGENT GALVANOMETER.
FIG. 74.—ROUGH SKETCH OF THE LINES OF FORCE IN TANGENT GALVANOMETER.

(This adjustment is commonly made by the manufacturer.) A current is passed through the coil, and the lines of force due to this current now combine with those of the earth to produce a figure similar to Fig. 74. The needle points along the resultant lines, which run more nearly east and west in proportion as the current strength is greater. The current is now reversed so that the lines of force are inclined in the other direction, and the average reading of the needle in the two positions is taken as the true deflection.

186. Theory of the Galvanometer. Unit Current.—To be able to calculate from this deflection the strength of the current we will employ the rules given on p. 131. These rules give the law by which the force varies with circumstances. To form an equation we shall need to define what is meant by unit current.

A unit current in a wire of a length of one centimeter and placed one centimeter distant from a unit magnetic pole will exert upon it a force of one dyne.

Combining this definition with the laws already cited, the intensity of the force at the center of the galvanometer coil is

$$F = \frac{il}{r^2},$$

where i is the current strength, l is the length of the wire, and r the distance from the wire to the needle. Commonly the coil is circular, and if it contain n turns of wire, $l = 2\pi rn$.

$$\therefore \quad F = \frac{2\pi ni}{r}.$$

Now if the intensity of the earth's force is called $\mathcal{H}$, the direction of the resultant intensity as calculated from the parallelogram of forces * is

$$\frac{F}{\mathcal{H}} = \tan \delta,$$

where δ is the angle between the magnetic meridian and this resultant; or

$$\frac{2\pi ni}{r\mathcal{H}} = \tan \delta,$$

whence

$$i = \frac{r}{2\pi n}\mathcal{H} \tan \delta.$$

We see that the current strength is not proportional to the angle of deflection, but to the tangent of this angle, whence the instrument is known as a tangent galvanometer.

187. Certain Precautions.—The coil of wire is usually of large radius, so that it may be accurately measured, while the needle should be very short, because the equation applies only to a point at the center of the coil. All the

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* Lodge's Mechanics, p. 96.

quantities in the equation for the current can be accurately determined except $\mathcal{H}$. The value of this (the magnetic intensity of the earth) is not only difficult to measure, but is also subject to frequent changes, as described in connection with the earth's magnetism; and in addition to this it is affected by the presence of magnets or of iron (steam and gas pipes, electric cars in the vicinity).

The quantity $\frac{r\mathcal{H}}{2\pi n}$ is sometimes known as the "constant" of the galvanometer. When once determined for any instrument, if we neglect these variations of $\mathcal{H}$ we need only multiply the tangent of the angle of deflection at any instant by this constant to know the strength of the current flowing in the coil at that instant.

188. Sensitive Galvanometers.—While fairly convenient for some purposes, this galvanometer is entirely useless for measuring the extremely feeble currents frequently met with in physical experiments. To increase the sensibility the first step is to bring the wire as close as possible to the needle, and wind it in many turns about the needle. The next step is to free the needle as far as possible from the controlling influence of the earth. (Examine the equation for the current strength and notice that with a given current δ is greater as $\mathcal{H}$ is less.) This may be done by bringing magnets near the needle to neutralize the earth's mag-

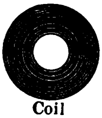

FIG. 75.—COIL OF SENSITIVE GALVANOMETER.

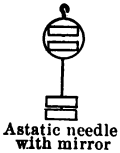

FIG. 76.—ASTATIC NEEDLE WITH MIRROR.

netism, but is much more perfectly accomplished by using the "astatic needle."

189. The Astatic Needle.—This consists of two needles (or sets of needles), Fig. 76, fastened to a vertical wire. One needle has its north pole in one direction, and the other has its north pole is the opposite direction. If the needles are equally magnetized, the north pole of one needle will be drawn north just as strongly as the north pole of the other, and if the poles point in opposite directions, the combination will stand one way about as readily as another. Some little imperfection in adjustment will always cause the needle to point one way rather than another, but the directing force will be slight. The coil of wire must surround but one of the needles, or sets of needles, but a second coil with the wire wound in the opposite direction may be wound about the second needle if desired.

190. The Mirror Galvanometer.—The sensitive galvanometer is always provided with a reflecting mirror and scale, as described on p. 68, in connection with the quadrant electrometer. In the instruments constructed by Kelvin, the mirror with the needles attached weighs about $\frac{1}{30}$ gram. Much lighter ones are constructed for special work, and the sensibility of some of them is almost beyond conception. To avoid the torsion of the fine silk fibre by which the needle is suspended (which is so fine as to be nearly invisible) Prof. Boys has introduced a still finer fibre drawn out from fused quartz, and this has come into extensive use for galvanometers and other delicate apparatus.

A mirror galvanometer constructed by Snow for special researches with the bolometer would detect a current so feeble that it would require a million years to decompose one drop of water. This current is about $\frac{1}{20000000000}$ as strong as that used in the ordinary incandescent light.

191. D'Arsonval Galvanometers.—The tendency of a coil of wire to turn so as to include the greatest possible number of lines of force has been utilized for producing a new type of sensitive galvanometers. In the D'Arsonval galvanometer the magnets are fixed, while the coil carrying the current is free to turn. This requires the coil to be light, but on the other hand the magnets may be large and powerful. The current enters the suspended coil by a fine wire or flat strip of metal which also serves to suspend the coil. A second wire or strip, serving to make electrical connection with

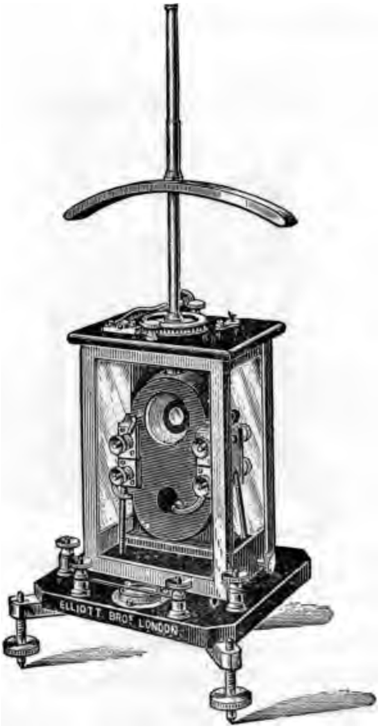

FIG. 77.—MIRROR GALVANOMETER.

the other end of the coil, runs to the base of the instrument.

These instruments have not reached the extreme delicacy of some of the galvanometers previously mentioned, but may be made sensitive enough for most work and are extremely easy to work with, allowing measurements to be made rapidly and accurately.

FIG. 78.—D'ARSONVAL GALVANOMETER.

192. Ballistic Galvanometers. — It is not infrequently necessary to measure a current which lasts but an instant. Thus Faraday showed * that the effect of a current of electricity on a magnetic needle was proportional to the quantity of electricity flowing (p. 131), by discharging a Leyden jar through the galvanometer, the jar being charged by a definite number of turns of his electrical machine.

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* Experimental Researches, vol. I. p. 103.

When used in this way the instrument is known as a ballistic galvanometer.

Any sufficiently sensitive type may be so used provided the needle does not have its motion too much retarded by air currents, electrical damping due to induced currents in the coil, etc.

When used in this way the deflection of the needle is only for a moment. As soon as it reaches the end of its swing it returns, vibrating like a pendulum about its position of rest.

If the whole current passes before the needle has moved an appreciable distance from its position of rest, the whole quantity of electricity passing through the instrument is *

$$Q = \frac{\mathcal{H}}{G} \frac{\tau}{\pi} \sin \frac{\delta}{2}.$$

---

* The proof of this equation requires the application of the laws of rotating bodies.

Let K be the moment of inertia of the needle;

$\mathcal{M}$, its magnetic moment;

and ω, its angular velocity.

Since the current all passes before the needle moves appreciably, the moment of the impulse is equal to the moment of momentum of the needle, or

$$K\omega = Q\mathcal{M}G.$$

Also, the kinetic energy of the needle at starting is the same as its potential energy in its extreme position, or

$$\tfrac{1}{2}K\omega^2 = \mathcal{M}\mathcal{H}(1 - \cos \delta) = 2\mathcal{M}\mathcal{H} \sin^2 \frac{\delta}{2}.$$

$$\therefore \quad K^2\omega^2 = 4\mathcal{M}\mathcal{H}K \sin^2 \frac{\delta}{2}$$

and

$$K\omega = 2 \sin \frac{\delta}{2} \sqrt{\mathcal{M}\mathcal{H}K} = 2\mathcal{M}G;$$

δ is the angular deflection of the needle, and τ the time of one complete swing to and fro. $\mathcal{H}$ has the same meaning as on p. 136. G stands for the expression $\frac{2\pi n}{r}$.

If the deflection of the needle is so small that the sine of the angle is nearly equal to the angle itself (as is frequently the case with mirror galvanometers), then

$$Q = \frac{\mathcal{H}}{G}\frac{\tau}{2\pi}\delta.$$

193. The Electrodynamometer. — An instrument for measuring currents which has proved of the greatest value in some very careful researches is Weber's electrodynamometer. Fig. 79 shows the apparatus as used by Weber in his original work on the measurement of currents. It has no suspended needle like a galvanometer, nor has it fixed magnets like the D'Arsonval; but there are two coils, one within the other, and these coils are at right angles to each other. The inner coil is hung by two very fine wires which also serve to conduct the current to the coil.

Suppose a current sent through the larger (fixed) coil, and at the same time through the suspended coil; then in order to embrace as many lines of force as possible the latter will endeavor to turn so as to be parallel with the former.

$$Q = 2\sin\frac{\delta}{2}\frac{1}{G}\sqrt{\frac{\mathcal{H}K}{\mathfrak{M}}}.$$

But

$$\tau = 2\pi\sqrt{\frac{K}{\mathcal{H}\mathfrak{M}}},$$

and using this to eliminate $\sqrt{\frac{K}{\mathfrak{M}}}$,

$$Q = \frac{\mathcal{H}}{G}\frac{\tau}{\pi}\sin\frac{\delta}{2}.$$

The force between the coils will be a measure of the current strength and may be determined in either of two ways: first, by the angular deflection of the coil; or second, by turning the top of the tube from which the coil is hung and measuring the amount of twist necessary to bring the coil back to its original position. It is ordinarily measured in the second way.

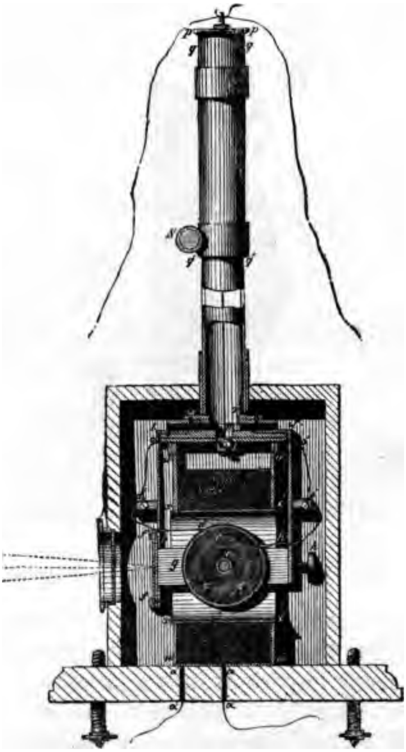

FIG. 79.—WILHELM WEBER'S ELECTRODYNAMOMETER.

194. Advantages of the Electrodynamometer.—This instrument has several marked advantages over a galvanometer. First, its indications are quite independent of the earth's magnetic force, and since this is the most uncertain factor in galvanometer measurements, it is capable of greater precision and has therefore been adopted for absolute measurements in many important investigations.

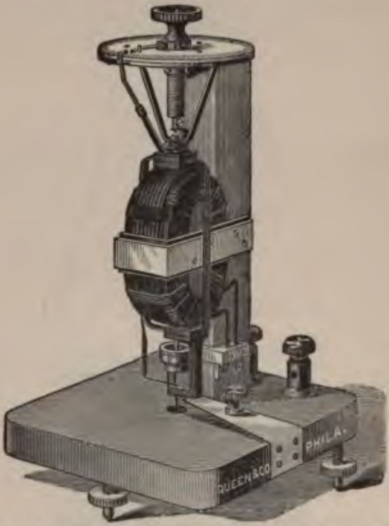

FIG. 80.—ORDINARY ELECTRODYNAMOMETER.

Second, reversing the direction of the current in either coil alone will reverse the direction of the deflection; therefore if the current in both coils is reversed, the deflection is not reversed. The instrument can therefore be used to measure currents which are reversed in direction many times a second; and as such currents have come into extensive use for electric lighting, the electrodynamometer has a wide field where the ordinary galvanometer is quite useless.

With an alternating current the galvanometer-needle would receive an impulse toward one side immediately followed (when the current is reversed) by an equal impulse toward the other side; the total effect being that the needle stands still.

195. Kelvin's Ampere Balances.—Similar to the electro-dynamometer in their action are Kelvin's balances (Fig. 81). In these instruments a coil of wire is placed on each end of an arm. The arm is hung by a set of fine wires so that it is free to move like the beam of a balance. Two fixed coils are placed parallel to each of these movable coils, one above and one below, as shown in the diagram Fig. 82.

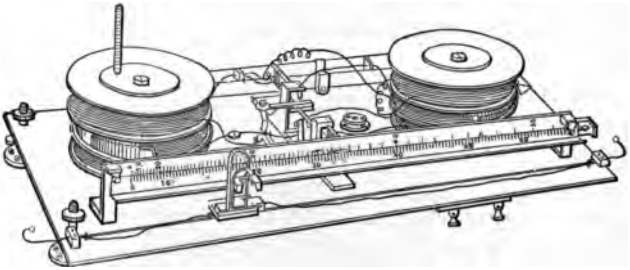

FIG. 81.

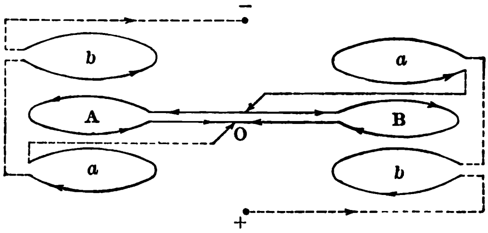

FIG. 82.

The current to be measured is carried through all six coils, reaching the movable coils through the suspending wires, which are so connected that the left end of the beam sinks and the right end rises. A small weight can be slid along the beam, and is moved to the right until the beam is in exact equilibrium, when its position is read off. The strength of the current is determined from the reading by reference to a table.

There is a series of these instruments made, so that any currents may be measured by them from very strong to quite weak. They have the advantages of the electro-dynamometer and at the same time are fairly portable and easily handled.

196. Ammeters.—The modern applications of electricity demand measuring apparatus that can be put into the hands of ordinary workmen and from which the value of the current strength may be read as easily as the pounds on an ordinary spring-balance. For much work these instruments must be portable and give correct readings when laid on a table or held in the hand.

Fig. 83 shows an ammeter based upon the principle of the D'Arsonval galvanometer. The coil is held between

FIG. 83.—WESTON PORTABLE AMMETER.

the poles of a horseshoe magnet and moves on jewelled bearings, while two springs, like the hair-spings of a watch, carry the current to the coil and also oppose the force of the current, which therefore rotates the coil more or less according to the strength of the current. A pointer attached to the coil moves over a scale upon which the number of amperes corresponding to each position of the pointer is indicated.

An ammeter suitable for station work is shown in Fig. 84. Since this is to be left in place, it can utilize the force of gravity to bring the arm back to its proper position, while the very strong currents to be measured require but few turns of wire—or rod—to exert sufficient force. The current is sent through the coil, and this then sucks the soft iron rod by a force depending on the strength of the current. A pointer moving over a scale indicates the force of

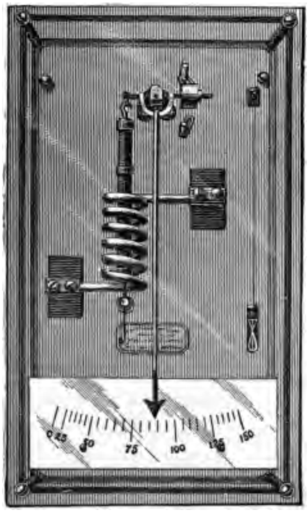

FIG. 84.—WESTINGHOUSE AMMETER.

this suction and therefore the strength of the current. Like all other ammeters it has a scale marked so as to read off the number of amperes passing through the coil.

These two may serve as samples, but the growth of electric industries has called hundreds of varieties of ammeters into existence, each manufacturer having a special design of his own.

An excellent method for the indirect measurement of strong currents will be found in § 206, p. 154. See also § 210, p. 161.

CHAPTER XIV.

MEASUREMENT OF RESISTANCE.

197. Resistance-boxes.—The effect of resistance on electric currents was described on p. 119. "In the present state of electrical science, the determination of the electrical resistance of a conductor may be considered as the cardinal operation in electricity, in the same sense that the determination of weight is the cardinal operation in chemistry." *

The determination of resistance ordinarily consists in a comparison of the thing whose resistance is sought with standard coils whose resistance is known.† These standards are commonly arranged in a series, the set being placed in a box, as shown in Fig. 85. The box is connected to the wires of the circuit in such manner that the current is obliged to pass through the brass bars on the top of the box; the resistance of these bars is generally considered to be zero. The gaps between the bars are bridged over by brass plugs, and when clean, the resistance of these may also be neglected. When a plug is removed, the current is obliged to go through a coil of wire in passing from one bar to the next. Thus by removing the appropriate plugs any coils may be placed in the circuit. The coils have different resistances, their values being arranged exactly like those

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* Maxwell's Electricity and Magnetism, vol. I. § 335.

† The methods given in this chapter are simply for the comparison of resistances. Methods for measuring resistances in C. G. S. units will be found in Chapter XXVII.

of the weights in a set of weights, so that any desired resistance may be obtained by a suitable combination of coils. A plan showing this arrangement is given in Fig. 86.

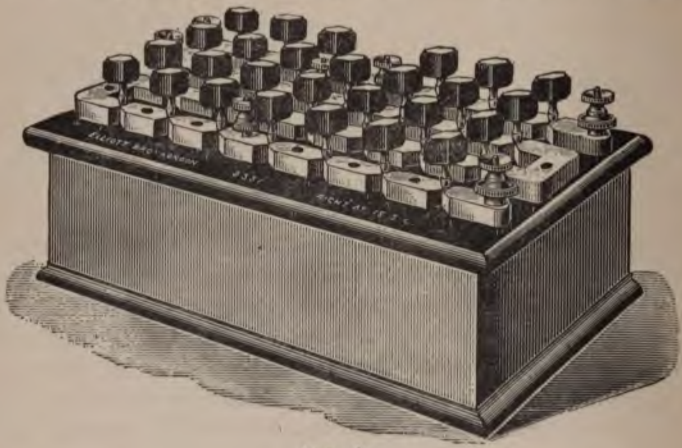

FIG. 85.

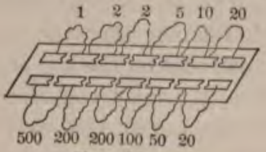

FIG. 86.

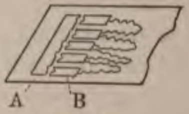

FIG. 87.

Another arrangement of coils is shown in Fig. 87. In this arrangement there are usually ten 1-ohm coils, ten 10-ohm, ten 100-ohm, etc. As this requires a much smaller number of plugs, it therefore lessens the danger which arises from dirty plugs and poor contacts. For suppose the wires of the circuit to be connected at *A* and *B*; then if a plug is inserted in the nearest hole, the resistance is 0; if in the fifth hole, it is 4, etc., and one plug suffices for each set of ten.

198. Standard Coils.—Where standards of high accuracy are required it is necessary to take account of the exact temperature of the coil. A coil well adapted to this purpose is shown in Fig. 88. The wire is coiled in the disk-shaped box at the bottom, and copper rods pass up from it for the purpose of making connections. The coil is placed in a jar of water, and the temperature of the water is taken as that of the coil.

FIG. 88.—FLEMING'S FORM OF STANDARD RESISTANCE COIL.

199. Resistance of Metals and Alloys.—The chart on p. 122 gives the specific resistance of different substances and shows the change of resistance when the temperature increases. It will be seen that the alloys have a higher resistance and change less with the temperature, and are therefore much better materials for the construction of standards. The cheaper boxes employ German silver, and the more expensive standards are of platinum-silver. Platinoid and several other alloys have recently come into use, and some of these have an extremely small temperature change of resistance.

200. Comparison of Resistances. — To compare such standard resistances with a wire or other conductor, and thus determine the resistance of the latter, one method has come into nearly universal employment, viz., that which uses Wheatstone's bridge.

201. Wheatstone's Bridge.—This apparatus depends for its use on the principle developed on p. 121, that when the electric current flows along a wire there is a falling off in the electrical pressure and that this fall of pressure is just proportional to the resistance which the wire offers to the conductor.

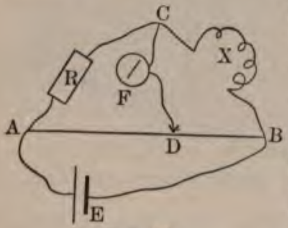

FIG. 89.

A diagram of the apparatus is shown in Fig. 89. The current from the cell at E divides and flows to B by two paths, ACB and ADB, and accordingly the pressure falls off equally along the two lines. Let A B be a uniform wire, then along this wire the pressure falls off uniformly; but along ACB it falls off just in proportion to the resistance in AC and CB. Therefore to find the ratio of the resistances AC and CB we need only find the relative fall of pressure in each. Connect a sensitive galvanometer F to the point C and slide the wire connected to the other terminal along the wire ADB until a point D is found which has the same pressure as the point C (determined by the fact that if the pressure at C is the same as at D no current will flow and the galvanometer will show no deflection). Then the resistance AC : resistance CB = resistance AD : resistance DB; and as the resistance of the wire ADB is proportional to its length, res. AC : res. BC = length AD : length DB. Therefore if a standard coil or a

FIG. 90.

resistance-box is placed in the arm AC, any unknown resistance CB may be compared with it.

202. Slide-wire Bridge.—Fig. 88 shows a piece of apparatus designed for this measurment. The thin line is a wire of German silver or other suitable alloy. The thick strips of copper at the back for making connections have so small resistance that no fall of pressure is supposed to take place along them.

203. Box Bridge.—It is not necessary to use a wire ACB. The four resistances are always in the ratio as above stated, viz., $\frac{AC}{CB} = \frac{AD}{DB}$; and so long as the value of one resistance and the ratio of two more is known, the value of the fourth can be determined. For commercial work the resistances are taken from coils suitably located in a resistance-box, while for accurate laboratory determinations they are specially wound coils protected from temperature changes and arranged so as to be readily interchanged in order to eliminate any difference between them.*

204. Insulation Tests.—While measurements by Wheatstone's bridge are of extreme accuracy, the method is not adapted to measure very large or very small resistances.

To test the insulation of wires and similar high resistances the current from a number of cells is sent directly through the galvanometer connected in series with the battery and conductor whose resistance is to be determined. The galvanometer deflection is observed and compared with that obtained when the unknown resistance is replaced by one of known value. The resistances are then in the inverse ratio of the two currents. Ordinarily the resistance of the battery and galvanometer may be neglected or a rough correction made for it.

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* For further discussion of the theory of this most important determination, see Gray's "Absolute Measurements in Electricity and Magnetism," vol. I. chap. vi.

205. Small Resistances.—For the measurement of very small resistances a number of methods have been employed based upon the fall of pressure, but avoiding the resistance of the connections necessary in Wheatstone's bridge.

Thus, a measured current may be passed through the strip *AB*, whose resistance is sought. A sensitive, high-resistance galvanometer is touched to two points near the ends of the strip and the deflection is observed. The galvanometer must then be "calibrated," i.e., a known weak current must be passed through it to determine the meaning of its readings in amperes. This is sufficient to give the resistance of the strip between the electrodes of the galvanometer, and the contact resistance where the current enters the strip is of no importance.

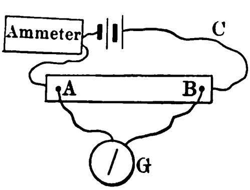

FIG. 91.

206. The Current may be Measured in the Same Way.—The same arrangement can be used for the measurement of the current in the circuit *ABC* if the resistance of the strip and the value of the galvanometer deflections are known. This is perhaps the best method for the accurate measurement of strong currents.

207. Battery Resistance.—Neither of these methods is adapted to measure the resistance of battery-cells or of any electrolyte, where polarization would entirely mask all effects of true resistance. Two methods are given for measuring the resistance of cells. The first can be used only for such cells as do not polarize readily when a current passes. The second may be applied to any cell and to any electrolyte, or, indeed, to any conductor whatever.

208. First Method.—Measure the electromotive force of the cell while on open circuit (a voltmeter as described in the next chapter may be employed for this purpose). Let this be found to have any value, say *E*. Again, measure the difference of presssure of the poles when the current is flowing through a wire of known resistance, say r; let this be found equal to E'. Now the current in the second case is produced by the electromotive force E in the circuit, whose resistance is that of the wire and battery combined, or

$$C = \frac{E}{R+r}.$$

It is also produced by the electromotive force E' in the wire whose resistance is r. Therefore

$$C = \frac{E}{R+r} = \frac{E'}{r},$$

and

$$\frac{E}{E'} = \frac{R+r}{r},$$

from which the battery resistance, R, is readily calculated.

If the battery polarizes easily, the electromotive force is less when the current is flowing than before and E as measured is too large. In this case the resistance may be measured as follows.

209. Second Method.—Arrange a Wheatstone's bridge with the battery to be tested occupying the place of the unknown resistance. In place of the usual battery put the secondary circuit of an induction coil (see p. 268), and in place of the galvanometer put a telephone. The induction coil furnishes a vibratory current of electricity, and such a current produces a noise in the telephone. A steady current does not. Now if the coils are adjusted in the proper ratio the current from the induction coil will not pass through the telephone and no noise will be heard. The advantage of the telephone is that it distinguishes between the current from the induction coil and that from the battery itself.

210. Applications of Resistance Measurements.—The readiness and accuracy with which measurements of resistance may be made, adapt them to the determination of temperature. The resistance of metals varies very appreciably with a change of temperature (see chart on p. 122); therefore the measurement of the resistance of a wire whose resistance has been previously determined will indicate its temperature.

211. Siemens' Pyrometer.—The Siemens pyrometer is an instrument for measuring the temperature of the hot gases of blast-furnaces and similar places which are much above the boiling-point of mercury and therefore beyond the range of the mercury thermometer. It consists of a coil of platinum wire wound upon a cylinder of fire-clay. This is placed in the furnace where the temperature is to be measured, and its resistance is then determined. A table is furnished with the instrument showing the temperature corresponding to each resistance.

The construction of this table presents the principal difficulty, as all measurements of high temperatures are difficult and few are entirely satisfactory.*

212. Underground Temperature.—The same method is valuable for determining the temperature of inaccessible places. Thus, to find the temperature of the earth ten, twenty, or fifty feet underground at different seasons of the year, a coil of wire of known resistance may be buried at these depths, and the measurement of its resistance will at any time give the temperature of the spot.

213. The Bolometer.—Perhaps the most remarkable use of this method is its employment for detecting very minute differences of temperature. Callendar makes a thermometer on this principle which will measure temperatures to .0001

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* For a comparison of different methods of pyrometry see the excellent summary by Barus in the U. S. Geolog. Survey, Bull. 54, p. 23.

degree, and Langley upon the same principle constructs his "bolometer," an instrument for measuring the heating power of different radiations. In this a fine strip of metal or of carbon is made to form one arm of a Wheatstone's bridge; the coils forming the three other arms are protected from temperature changes, but this fine wire forming the first arm is exposed successively to the radiations to be measured, and the amount of heating is determined by the current sent through the galvanometer by the disturbances of the balance in the ratio of the coils. In the recent forms of this instrument Langley records the galvanometer deflections by photography,* securing in a few minutes measurements which required years of painstaking labor with his earlier apparatus.

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* *Nature*, Nov. 1, 1894.

CHAPTER XV.

MEASUREMENT OF ELECTROMOTIVE FORCE.

214. Measurement of Electromotive Force. — Electromotive force is anything that tends to set up a flow of electricity. In any metallic circuit, like a wire, which does not form part of the armature of a dynamo or other source of electromotive force, this electromotive force is due to the difference of electrical pressure of the different parts of the wire.

Hence to measure the electromotive force between two points on a conductor we may either measure this difference of pressure directly, or we may measure it indirectly, by finding how much current it produces in a suitable resistance. The following methods should be mentioned.

215. Methods of Measurement—First Method.—Since the quadrant electrometer (p. 65) measures directly the difference of pressure on its quadrants, we may connect the two parts of the circuit between which we are measuring the electromotive force, one to each pair of quadrants. A deflection of the needle is thus obtained which must be compared with that produced by a standard cell connected in the same way. This method requires no current to flow, and may therefore be used for cells which polarize very easily. It is not extremely accurate, and the apparatus is expensive and difficult to use.

216. Second Method.—We may measure the current produced through a known resistance and calculate the electromotive force by Ohm's law,

$$E = iR.$$

Here we must remember to include the resistance of the galvanometer, battery, and any other conductors through which the current flows. If, however, the resistance of the galvanometer is sufficiently great, that of the cells and the rest of the circuit may be neglected. Thus if different cells are successively connected to such an instrument, the currents will be proportional to the electromotive forces of the cells. A high-resistance galvanometer thus used is called a " potential galvanometer."

217. Third Method.—The following method is excellent and requires no current to pass through the cell; for definiteness I will assume that the electromotive forces of two cells are to be compared. A current from a battery of several cells, *L*, Fig. 91, is sent through a uniform wire *AB*. The cells which are to be compared, *D* and *E*, are connected through a galvanometer *G* to the point *A* on the wire. At *C* a key which is attached to one pole of the cell *D* makes a contact with the wire *AB* at such a point on it that no current passes through the galvanometer when the contact is made. A similar key at *C′* performs the same duty for the cell *E*. In the experiment it is necessary that all the poles of the different cells connected to *A* should be of the same kind, say copper.

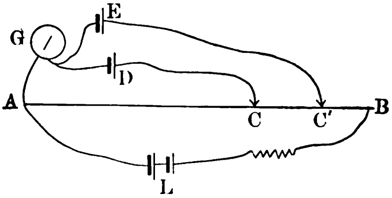

FIG. 92.

The theory of the experiment is as follows: There is a uniform fall of pressure along the wire from *A* to *B*. There is also a fall of pressure from the copper to the zinc pole of the cell D. The copper pole of D is at the same pressure as the point A of the wire; and if the point C is so selected that closing the key causes no current to flow, it is because the pressure at C is the same as that of the zinc pole of D. Therefore the fall of pressure along the wire is the same as the difference of pressure of the two poles of the cell. Apply the same reasoning to the cell E and it is plain that for the ratio of the electromotive forces we have

$$\frac{\text{E.M.F. of } D}{\text{E.M.F. of } E} = \frac{\text{Fall of pressure } AC}{\text{Fall of pressure } AC'} = \frac{\text{length } AC}{\text{length } AC}$$

In practice the uniform wire AC may well be replaced by two resistance-boxes R and R', and instead of shifting the point C the adjustment is made by changing the resistances R and R' till equilibrium is obtained as before. The sum $R + R'$ should be maintained constant in order that the current may not change, and if this condition is satisfied, then as before

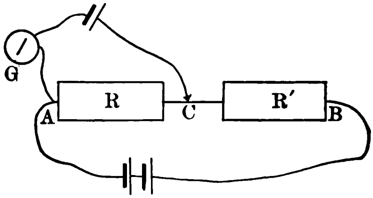

FIG. 93.

$$\frac{\text{E.M.F. of } D}{\text{E.M.F. of } E} = \frac{R_1}{R_2},$$

where R_1 and R_2 are the values of the resistance R necessary to produce balance with the cells D and E respectively.

218. Standard Cells.—These methods give the comparative electromotive forces of two cells. If the actual value is desired, it is necessary to use for comparison some cell whose electromotive force is known. Several such cells have been invented, of which the best is Clark's. This consists of a platinum wire covered with mercury for the positive pole; the mercury is covered with mercurous sulphate, over this is a solution of zinc sulphate in which the zinc pole is immersed, and the whole sealed up. Rayleigh's directions for preparing the cell and a study of its behavior are given in Philosophical Transactions, Part II, 1885; and a further description and directions based upon the work of the Physicalische Reichs-Anstalt of Berlin is found in the London *Electrician* for July 7, 1893.

219. Use of the Same Method to Measure Currents.—The perfection reached in the construction of these cells and the readiness with which they may be made gives them great value for standardizing apparatus, and I will therefore describe a method of measuring currents based upon exactly the principle just described.

Let the current to be measured flow through a piece of wire (or resistance coils) *AB*, Fig. 94, as before, and let *D* be a Clark standard cell. Then adjust the point *C* (or the resistance *AC*) until no current flows through *G*, when contact is made. Let the resistance *AC* equal *R*, and the current to be measured *i*, while the electromotive force of the cell is *E* ;* then

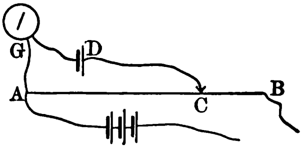

FIG. 94.

$$i = \frac{E}{R}$$

and the measurement of the current requires only a measurement of resistance, and may be made with very great accuracy.

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* The cell constructed as described in the place cited has an E. M. F. of 1.438 volts at 15° C., and increases .00115 volt for each degree.

220. Voltmeters.—Instruments for the commercial measurement of electromotive force or "voltage" of circuits are known as "voltmeters." They differ from potential galvanometers only as ammeters differ from ordinary galvanometers; viz., they are portable and they are graduated directly in volts. One of the best is similar to the ammeter described on p. 146, but has a high resistance and is more sensitive to weak currents. When this is connected to the two points whose difference of pressure is to be measured, a current flows which is proportional to that difference of pressure. When a current flows which is due to a pressure of one volt the pointer moves to a point which is marked 1, and similarly for two, three, etc., volts.

Lord Kelvin has constructed a modification of his quadrant electrometer to be used as a voltmeter. In this (the "multicellular voltmeter") a series of needles like those of the quadrant electrometer are fastened, one above the other, to the same vertical wire between metal plates which act as "quadrants." In use the needles are connected to one terminal and the plates to the other. Whatever difference of pressure may exist between the terminals will then cause a corresponding charge upon the plates and needles,

FIG. 95.—WESTON VOLTMETER.

causing an attraction between them; and the needle will be deflected from its normal position. The difference of pressure is indicated on a graduated scale by the pointer connected with the needles.

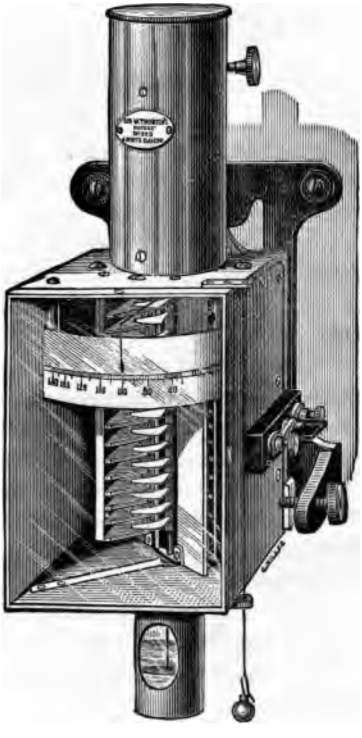

FIG. 96.—MULTICELLULAR VOLTMETER.

Another kind of voltmeter is described on p. 176, which depends for its action upon the heating effect of the current.

CHAPTER XVI.

ELECTROMAGNETIC UNITS.

221. The Electromagnetic System. — A discussion of electrostatic units and their dimensions was given on p. 72. Several of the units involved in current measurement have already been given, but it will be convenient to collect these in a single chapter. All the units of measurement which are based upon the force exerted between two charged bodies are known as electrostatic units. Those which depend upon the force exerted by currents upon currents or upon magnets are called electromagnetic units, and the corresponding system is called the electromagnetic system.

222. Definitions.—Current.—A unit current in the electromagnetic system is that current which, flowing through an arc of a circle one centimeter long and whose radius is one centimeter, exerts a force of one dyne upon a unit magnetic pole at the center of the circle.

This unit is seldom used even by scientific men. In its place is employed a " practical " unit called the ampere. The ampere is one-tenth as large as the absolute C. G. S. unit just defined.

Quantity.—The unit of quantity in this system is that quantity which passes any point on a wire in one second when a unit current flows in the wire.

The corresponding practical unit is one-tenth of the C. G. S. unit, and is called the coulomb.

Electromotive Force.—The unit of electromotive force, or difference of potential of two points, is that which requires one erg of work to be done in order to carry a unit quantity of electricity from one point to the other.

Since the erg is a very small quantity of work, while the unit of electrical quantity is quite large, this unit is much too small for practical use, and in its place is employed a practical unit which is one hundred million (10^8) times as large, which is called the volt.

The amount of work required to carry one coulomb of electricity from one point to another which has its potential one volt higher than that point is called a joule.

Resistance.—The unit of resistance is such a resistance as requires a unit difference of potential between its ends to maintain a unit current through it.

As in case of the volt, the practical unit is much larger. The practical unit is one thousand million (10^9) C. G. S. units, and is called the ohm.

Power.—A current of one ampere flowing through one ohm performs one joule of work per second.

One joule per second is called one watt. The watt, like the horse-power, is a certain number of units of work per second. The watt is $\frac{1}{746}$ of a horse-power.

Capacity.—A condenser has a unit capacity if a unit quantity of electricity given to it raises it to unit potential.

The practical unit of capacity is one thousand-millionth of the C. G. S. unit and is called the farad.

A globe to have a capacity of one C. G. S. unit would require to have a diameter of eleven thousand million million miles, or say 500 times the distance to the nearest fixed star. The farad itself, being the capacity equal to that of a sphere of over ten million miles in diameter, is ordinarily replaced by the microfarad, which is one millionth of a farad and which is of a magnitude similar to those actually occurring in practice.

223. The "International" Units. — In order to give these practical units such definitions as to make them available for ordinary commercial purposes, and for proper legislation, several national and international bodies have attempted to reduce them to material standards. The name "international" units has been formally applied to these units as defined by the World's Electrical Congress in Chicago in 1893, and since legalized in several countries. According to this definition * the international ohm is considered equal to the resistance of a uniform thread of mercury at 0° C. weighing 14.4521 grams and 106.3 cm. long. (This would have a cross-section of just about 1 sq. mm.)

The international ampere is considered to be a current that will deposit silver from the solution of the nitrate at the rate of .001118 grams per second.

The international volt is equal to $\frac{1000}{1434}$ of the electromotive force of the Clark standard cell at the temperature of 15° C.

The other units are derived from these in the manner indicated in their definitions; thus the international coulomb is the quantity of electricity passing a point in a wire when an ampere as above defined flows for one second.

There is no necessity for writing out rows of ciphers like those occurring in the above quantities and in many other branches of Physics. It is customary to use what is called the "index rotation," by which the number of ciphers is expressed as the exponent of 10. Thus, one million is 10^6, and three millionths is 3×10^{-6}. Using this notation, the ratio of the C. G. S. and practical units is shown in the table p. 168.

The ordinary metric prefixes are used with these quantities; thus 1 centiampere = $\frac{1}{100}$ ampere. 1 kilowatt = 1000 watts or 1.34 horse-power. In addition, the prefix meg- or mega- indicates one million, and micr- or micro- stands for one millionth. Thus, 1 microfarad = one millionth of a farad, and 1 megohm means one million ohms.

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* See Bulletin 31 of the U. S. Coast and Geodetic Survey, August, 1894.

224. Dimensions.—The dimensions of the various electromagnetic units may be found exactly as were those of the electrostatic units, p. 72. Since the definitions are based upon the effect of the current upon a magnetic pole, we must first find the dimensions of pole strength.

Two poles act upon each other with a force proportional to their strength and inversely as the square of their distance, or

$$f = \frac{m^2}{r^2},$$

and

$$m = r\sqrt{f}.$$

The dimensions of force (p. 9), are LMT^{-2}, and those of m are found by dividing the exponents by 2 and adding 1 to that of L. Hence they are

$$m. \qquad L^{\frac{3}{2}}M^{\frac{1}{2}}T^{-1}.$$

The dimensions of current are found from the law that a current in a circular coil of circumference l acts upon a pole m at the center of the coil with a force indicated by the equation

$$f = \frac{mli}{d^2},$$

from which

$$i = \frac{fd^2}{ml}.$$

Substituting the above dimensions for f and m, and remembering that d and l have each the dimensions L, those of i are found to be

$$i. \qquad L^{\frac{1}{2}}M^{\frac{1}{2}}T^{-1}.$$

From the fact that quantity is the product of i by the time during which the current flows, its dimensions are

$$Q. \qquad L^{\frac{1}{2}}M^{\frac{1}{2}}.$$

Electromotive force multiplied by quantity represents an amount of work, or

$$W = QE,$$

$$E = \frac{W}{Q}.$$

Since work is the product of a force by a distance, its dimensions are

$$W. \qquad L^2MT^{-2},$$

and those of E

$$E. \qquad L^{\frac{3}{2}}M^{\frac{1}{2}}T^{-2}.$$

Since $R = \dfrac{E}{i}$, its dimensions are

$$R. \qquad LT^{-1}.$$

Capacity is found by dividing the quantity of charge by the potential resulting, and its dimensions are

$$C. \qquad L^{-1}T^2.$$

225. Tabulated Results.—The following table shows the relations of a number of the more important quantities.

	Name of Practical Unit.	Number of C. G. S. Units in 1 Practical Unit.	Dimensions in Electromagnetic System.	Dimensions in Electrostatic System.
Pole strength.......			$L^{\frac{3}{2}}M^{\frac{1}{2}}T^{-1}$	$L^{\frac{1}{2}}M^{\frac{1}{2}}$
Current............	Ampere	10^{-1}	$L^{\frac{1}{2}}M^{\frac{1}{2}}T^{-1}$	$L^{\frac{3}{2}}M^{\frac{1}{2}}T^{-2}$
Quantity............	Coulomb	10^{-1}	$L^{\frac{1}{2}}M^{\frac{1}{2}}$	$L^{\frac{3}{2}}M^{\frac{1}{2}}T^{-1}$
Electromotive force.	Volt	10^8	$L^{\frac{3}{2}}M^{\frac{1}{2}}T^{-2}$	$L^{\frac{1}{2}}M^{\frac{1}{2}}T^{-1}$
Resistance..........	Ohm	10^9	LT^{-1}	$L^{-1}T$
Capacity...........	Farad	10^{-9}	$L^{-1}T^2$	L

226. Ratio of Units.—A very curious fact is observed when the dimensions of the units in the two systems are compared, viz., that the ratio of the two involves LT^{-1} or the dimensions of a velocity. Thus, comparing the dimensions of quantity in the two systems, we find

$$\frac{L^{\frac{3}{2}}M^{\frac{1}{2}}T^{-1}}{L^{\frac{1}{2}}M^{\frac{1}{2}}} = LT^{-1}.$$

Similarly for capacity $\frac{L}{L^{-1}T^2} = L^2T^{-2}$, or the dimensions of v^2. Again, the dimensions of resistance give $\frac{L^{-1}T}{LT^{-1}} = L^{-2}T^2$, or the dimensions of $\frac{1}{v^2}$.

227. Numerical Value of the Ratio.—Further, the same quantity may be measured in both systems. Weber and Kohlrausch * measured the quantity of charge in a Leyden jar in electrostatic units and then, by discharging it through a ballistic galvanometer, measured it in electromagnetic units.

Kelvin † measured the difference of potential of two points on a wire in electrostatic units, and the current which it maintained in a wire in electromagnetic units.

Rosa,‡ by a Wheatstone's bridge-method, balanced the current produced by frequently discharging a condenser (at each vibration of a tuning-fork) against the current which the same electromotive force maintained in a high resistance.

All these experiments and many others have shown that the measurement of a quantity of electricity in electrostatic units is expressed by a number very nearly 3×10^{10} times

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* See Maxwell's "Electricity and Magnetism," vol. II. p. 380.

† Ib. p. 382.

‡ *Amer. Jour. of Sci.*, Oct. 1889, p. 298. Appended to his paper is given a list of ten determinations by different experimenters.

as large as when measured in the electromagnetic, showing that the unit of measurement in the latter case is 3×10^{10} times as large as in the former.

228. The Velocity of Light.—It can hardly be accidental that this number, 3×10^{10}, is almost exactly the velocity of light as determined by the most accurate experimenters. Maxwell showed that if any strain or disturbance such as we have assumed to take place in charging or discharging a conductor (see Chap. III) should really occur, this disturbance would travel through the ether with a velocity equal to the ratio of the units in the two systems (just as a wave starts out on the surface of a pond when a stone is thrown into the water). That this should turn out to be just the velocity of light goes far toward proving that light is an electrical vibration, and that electrical strains are disturbances in the luminiferous ether. A number of other facts point strongly in the same direction, and no doubt of such a connection between light and electricity is now found among scientific men.

Further facts bearing on this connection are given in Chapter XXIV.

CHAPTER XVII.

HEATING EFFECT OF THE CURRENT.

229. The Current Produces Heat.—Having studied the laws of the current and the methods of measurement, we are now in position to form clear and quantitative ideas of the various effects of the current.

On. p. 75 it was stated that the discharge of the Leyden jar would heat a wire red-hot, and that steady currents have the same power is daily demonstrated by the electric light. If the poles of a vigorous closed-circuit battery are connected by a short fine wire of iron or platinum, the wire is heated red hot, and the more powerful the battery, the thicker and longer the wire that may be so heated. The laws of this heating effect have been made the subject of careful experiment;* and they may be immediately inferred from the laws of the current as follows:

230. Laws of Heating Effect.—Let the difference of potential of two points *A* and *B*, Fig. 97, be $V_2 - V_1$. This means that it requires $V_2 - V_1$ units of work to carry a unit quantity from *B* to *A*, and conversely each unit quantity in flowing from *A* to *B* will do this amount of work. Now if a current

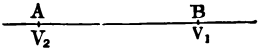

FIG. 97.

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* It was his experiments on the effect produced by electric currents and the amount of chemicals used in their production that led Joule to propound his momentous theory of the Conservation of Energy. See Reynold's Memoir of J. P, Joule.

i is flowing in the wire for a time t, the whole work done by the current in this time is

$$W = (V_2 - V_1)it,$$

or, since the electromotive force is equal to the difference of potential of the points,

$$W = Eit.$$

This is the work done by the current between A and B. It may be spent in heating the conductor, in driving a motor, or in any other process. If, however, it all goes to heating the wire, the number of heat-units, H, will be obtained by dividing the number of work-units by J, where J stands for the mechanical equivalent of heat (see p. 7). If the current and electromotive force are expressed in C. G. S. units, the mechanical equivalent must be given in terms of the energy in ergs required to warm a gram of water 1° C.; but if the practical units are used in the electrical measurement, this number must be divided by 10^7.

In this case the value will be $J = 4.27$; and since

$$W = HJ,$$

therefore

$$H = \frac{Eit}{J},$$

and the amount of heat developed per second measured in joules is

$$\frac{JH}{t} = Ei.$$

Ohm's law enables us to eliminate E and i in turn, thus giving, in all, three different expressions for the heat developed, viz.,

$$\frac{JH}{t} = Ei, \qquad (1)$$

$$= Ri^2, \qquad (2)$$

$$= \frac{E^2}{R}. \qquad (3)$$

231. Discussion of Results.—All three expressions contain the same truths, but ordinarily the second is the more convenient. It states that in any given wire the heat developed is proportional to the square of the current. This equation also states that any given current produces an amount of heating directly proportional to the resistance that it overcomes.

This can be very prettily shown by passing a current through a conductor made of successive pieces of wire, silver and platinum alternating. The platinum wires will glow brilliantly, and may even be melted, while the silver shows no visible signs of heating.

Corresponding conclusions may be drawn from each of the equations; thus the third shows that with a given difference of potential at its ends a wire of low resistance has more heat developed than one of high, etc.

All these facts have been abundantly verified by the experiments of Joule * and many more recent physicists. Indeed so accurate are the measurements, that the relation here shown between the electrical energy and the heat evolved affords an excellent method of determining J, the number of work-units in one heat-unit.

232. Commercial Applications.—The commercial applications of the heating effect of electrical currents have

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* Joule's Scientific Papers, vol. I. p. 60.

within a few years built up new and vast industries extending to every part of the civilized world.

233. Incandescent Lighting.—The incandescent electric light, which is in general use for interior illumination, consists of a thin carbon filament heated white-hot by the electric current. To prevent its immediate destruction by burning, the filament of carbon is placed in a glass globe from which all air has been carefully exhausted by a mercury air-pump.

Carbon cannot well be sealed into glass, hence the ends of the filament are attached to short pieces of platinum wire. These wires are passed through a closed tube of glass which is fused about them air-tight, and then the tube with attached filament is sealed into the glass bulb. To the outer ends of the platinum wires are attached the conductors which serve to bring the current from the battery or dynamo.

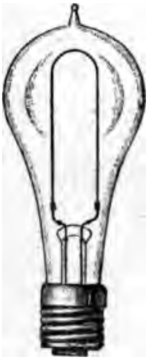

FIG. 98.

The ordinary lamp for private use in this country is of 16 candle-power, and at a pressure of 110 volts requires about ½ ampere. If the pressure is less, the current must be proportionately greater, the product *CE* always remaining equal to about 55.

234. Arc Lights.—The incandescent lamp is very satisfactory, but for lighting streets, railway stations, large warehouses, etc., a much more powerful light is used, which is much cheaper per candle-power, called the arc light. Sir Humphry Davy * discovered that if two pieces of carbon were connected to the two poles of a powerful battery and touched together and then separated slightly, the spark was much more brilliant than when wires were used. If the

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* Phil. Trans. 1821, p. 427.

pressure is 30 or 40 volts, the spark will continue as long as the carbons are held near together, and glows with great brilliance, forming what is known as the electric arc.

235. The Arc Lamp.—The carbons of the incandescent light are placed in a vacuum to prevent their combustion, but in the arc a constant evaporation and destruction of the carbon is necessary for the continuance of the action. Hence the carbons require renewal daily, and a special apparatus is required to bring them together as they are consumed. The first lamps for this purpose contained elaborate clockwork to feed the carbons at the required rate; the positive one advancing twice as rapidly as the negative, since it is used up about twice as fast. Although working fairly well, these lamps were expensive and delicate—not at all suited to the rough work of street-lighting. The modern lamp for this purpose is so constructed that the magnetic action of the current itself regulates the distance of the carbons. As the arc lengthens, more of the current flows through a coil of wire placed in parallel with the arc, and this coil acting as a magnet causes the carbons to come together.

FIG. 99.

The light comes principally from the crater in the positive carbon, which is heated to a dazzling whiteness by the current. The negative carbon is less brilliant, and the arc itself, though intensely hot, is less luminous. It is of a pale blue or violet color.

236. The Electric Furnace.—In addition to its use for lighting, the heat of the arc renders it very valuable in many metallurgical processes. It is used on an extensive scale for reducing aluminium from its ores, and several other interesting products are obtained by its means.

237. Electric Welding. — The heat developed by the passing of a current through a conductor is successfully employed for welding metals together. Two pieces of metal to be joined are pressed firmly together and an intense current is passed through them until they soften from the heat. They are then forced together and the current turned off. To weld a heavy strap of iron, say $\frac{3}{8} \times 1\frac{1}{2}$ inches, would require the current to pass for about 10 seconds; but the joint would then require finishing. Wires and rods of steel, aluminium, copper, and other metals are united in this way, and pieces as large as railroad-rails are readily joined. The joint is just about as strong as any part of the bar.

238. Miscellaneous Applications.—The heat of the current may easily be employed for heating houses, cooking, etc. The method is somewhat too expensive at present to be generally employed, though for special uses, such as heating electric cars, the current is often used. Surgeons also employ a wire heated to a white heat for cautery. A fuse for exploding dynamite is made by embedding a fine short wire in a cartridge containing fulminating powder; and this is not only a convenient way of setting off the charge, but also makes it possible to explode many charges at the same instant, as in removing the obstructions at Hell Gate.

239. For Electrical Measurements.—The heat produced by the current is employed as a measure of the current. An instrument in general use for this purpose is the Cardew voltmeter, Figs. 100 and 101. This is made as follows: A fine wire, *ABC*, is fastened to the inside of a long tube at one end, *A*, and then runs over a light wheel, *B*, and back to *C*. Here the wire is attached to a fine cord which passes over the wheel *D* and to a spring, *E*, by which the cord and wire are kept tight. At *A* and *C* wires lead to the circuit whose pressure is to be measured. A current flows through the wire *ABC* just proportional to the difference of pressure at the points *A* and *C*, and the wire is correspondingly heated; this causes it to lengthen, and the wheel *D*, carrying a pointer, turns to the number on the dial which represents the pressure in volts. (This description gives only the principle. The details differ in different instruments.) This voltmeter is very generally used for measuring the pressure of alternating currents which produce a heating effect, but which cannot be measured by galvanometers, nor by voltmeters based upon the effect of a current in acting upon a permanent magnet.

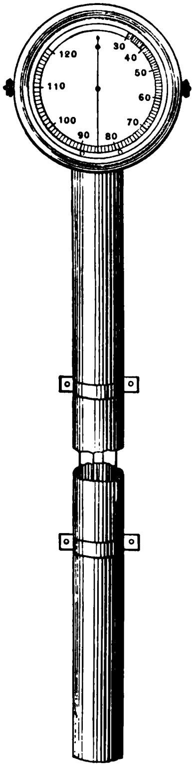

FIG. 100.

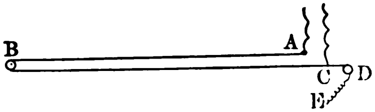

FIG. 101.

CHAPTER XVIII.

CHEMICAL EFFECT OF THE CURRENT.

240. Electrolysis.—In the year 1800, Carlisle and Nicholson discovered that water was decomposed when the electric current passed through it. We have already seen (p. 101) that zinc is dissolved and hydrogen is set free when an electric current passes through the acid of the voltaic cell.

Sir H. Davy * passed the current from 250 cells through caustic potash, and on one of the poles obtained some globules of a new metal as a result of the chemical decomposition of the potash; this metal he named potassium.

Nearly all liquids except the liquid metals are decomposed when the current flows through them. This process is called electrolysis, and such conduction is termed electrolytic; the substance decomposed is called an electrolyte, and the wires or conductors through which the current enters are called electrodes.† These names were introduced into the science by Faraday,‡ who followed up the experiments of Davy and determined several of the laws of this kind of conduction.

241. Laws of Electrolytic Conduction.—These laws are well established, viz.:

1. No appreciable flow takes place until the difference of pressure of the electrodes reaches a definite value (different for different electrolytes).

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* Davy. Phil. Trans., 1808.

† The positive electrode is known as the anode, and the negative as the cathode.

‡ Experimental Researches, vol. I. p. 196.

2. No slightest current can pass without chemical decomposition of the electrolyte.

3. "The chemical decomposing action of a current is constant for a constant quantity of electricity, notwithstanding the greatest variation in its sources, in its intensity, in the size of the electrodes used, in the nature of the conductors through which it is passed, or in other circumstances." *

This law Faraday proved by many careful experiments which showed—

a. That if the current passed successively through different vessels containing the same substance (acidulated water), the amount of decomposition was the same whatever the size of the electrodes or the strength of the current (Fig. 102).

b. That if the current were divided, part passing through one vessel (Fig. 103) and part through a second, then united so that all should pass through a third, the decomposition in the third would be equal to that in the first and second combined.

FIG. 102.

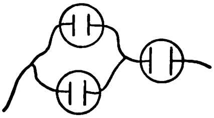

FIG. 103.

c. That if the same current passes through two substances, e.g., solution of silver nitrate and solution of silver chlorate, the same amount of silver is liberated in each. These laws are all included in another, which also calls attention to a remarkable relation existing between electrical and chemical forces. This law is that

Each unit quantity of electricity in passing through an electrolyte liberates an amount of each substance exactly proportional to the combining weight of that substance.

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* Exp. Res., vol. I. p. 207.

Thus if we connect three vessels in series so that the same current passes through all, the first containing water, the second a solution of copper sulphate, the third a solution of silver nitrate; then if we pass a current until 1 gram of hydrogen has been liberated in the first, there will be liberated 31.6 grams of copper in the second and 108 grams of silver in the third. But 31.6 grams of copper and 108 grams of silver are just the amounts of these metals that would replace 1 gram of hydrogen in any of its compounds.

242. Electrochemical Equivalents.—It is therefore possible to construct a table showing the quantity of any substance liberated by 1 coulomb of electricity. The relative combining weights of the elements are found by dividing their atomic weights by their valency. Hence when the electrochemical equivalent of one substance is ascertained, it is easy to find that of all substances whose atomic weight is known.

Name of Element.	Grams Liberated per Coulomb.
Aluminium	.0000935
Copper (cuprous*)	.0006556
Copper (cupric*)	.0003278
Gold	.0006808
Hydrogen	.00001039
Iron (ferrous*)	.0002900
Iron (ferric*)	.0001933
Lead	.001072
Oxygen	.0000829
Silver	.001118
Tin (stannous*)	.000611
Tin (stannic*)	.000306
Zinc	.000389

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* Where the same element has two different valencies it must be treated (as it is chemically) as two different substances.

This table has been constructed by taking the electrochemical equivalent of silver, found by Rayleigh* and Kohlrausch† to be .001118, and combining it with the atomic weights of the different elements as given in Ostwald's "Outlines of Chemistry."

243. Use of Table.—To apply this table we notice, e.g., that one coulomb liberates .00001039 gram of hydrogen. The number of coulombs for any current is found by multiplying the amperes by the time it flows (in seconds). Therefore the whole weight of hydrogen liberated by any current i is

$$W = .00001039 \times it,$$

and for any substance whose equivalent is e

$$W = eit.$$

244. How does Electrolysis Take Place?—The laws of chemical decomposition as stated are quite certain. Just how the action takes place is less certain. These laws show that one atom of any univalent element gives to the electrode just as much electricity as an atom of any other univalent element. Bivalent atoms give up twice this amount, and so on for other valencies. In decomposing, one of the products appears at one electrode, and the other at the other electrode. To account for the insensible passage of the "ions" or products of decomposition, Grotthus, in 1805, suggested that the atoms of the molecules were charged, and that the introduction of the electrodes turned the molecules with their positive atoms toward the negative electrode and the negative atoms toward the positive electrode. The electric forces then tore apart the molecules nearest them, while the intervening

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* Rayleigh (.00111794), Phil. Trans. 1884, Part II.

† Kohlrausch (.0011183), Wiedemann's Electricität, vol. IV. p. 981.

molecules rearranged themselves according to the diagram Fig. 103.

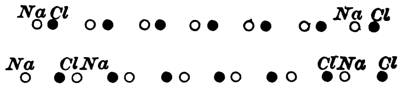

FIG. 104.—ELECTROLYSIS ACCORDING TO GROTTHUS' HYPOTHESIS.

245. Clausius' Theory.—This theory required a certain electric force to produce the decomposition, but experiment indicates very positively that while a certain electromotive force is required at the electrodes to compel the liberation of the ions, yet in the substance of the liquid, the slightest force can produce a corresponding current, as in metallic conductors.

Clausius[*] therefore added the assumption that by their mutual collisions more or less of the molecules were dissociated or broken up into the corresponding ions. Recent chemical study has gone to great lengths in this direction, and it is now confidently claimed that most salts are more or less dissociated, and some of them very completely, when dissolved in water. Thus if KCl is dissolved in water to form a very dilute solution, there is evidence that there are hardly any molecules of KCl in solution, but K and Cl atoms instead. These atoms are highly charged, each with a definite charge, and the process of electrolysis consists in drawing these charged ions to the different electrodes, where they give up their charges and are themselves deposited. Measurements of the electrical conductivity of dilute solutions show that it depends on the number of free ions thus present rather than on the amount of the salt dissolved.

246. Secondary Products of Electrolysis.—It is not often that the ions themselves appear at the electrodes; indeed it

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[*] On the nature of electrolysis see Ostwald's "Outlines of General Chemistry" (Walker's translation), p. 273; also the B. A. Reports for 1885 and 1886.

is often difficult to tell what the ions really are, either because they are unstable and decompose as soon as deprived of their charges, or else because they attack any substance present and form new compounds.

Thus if a current is passed through water containing a little sulphuric acid,* there will be liberated at one electrode hydrogen, and at the other oxygen, in the proportion in which they combine to form water. Yet it is certain that much, if not all, of the action is the electrolysis of H_2SO_4 into H_2 and SO_4. Of these two substances the 2H appears at the negative electrode, while the SO_4 at the positive electrode attacks the water present, forming H_2SO_4 and O. There is as much acid present in the solution at the end of the process as at the beginning, but the water is gradually used up. If the current is passed through sulphuric acid which contains no water, the action is much more complicated, sulphur, hydrogen, and several compounds being liberated.

247. The Current does not Produce Decomposition.— Evidently much of the difficulty which is met in studying the theory of electrolysis is caused by this doubt as to what the ions really are; yet the recent investigations referred to show that the current does not of itself produce any decomposition, and much light is thrown on the nature of all chemical action.

248. Applications to Electrical Measurements. — The chemical properties of the current lead to a wide range of usefulness. Faraday † pointed out the value of his discoveries for the purpose of electrical measurement, and, in the absence of any better unit, suggested that the quantity

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* The experiments of Kohlrausch show that the electrical resistance of *pure* water is very high, if it be not really a non-conductor. Slight amounts of impurity are sufficient to enormously increase its conductivity.

† Exp. Res., vol. I. p 739.

of electricity liberating 1 cubic inch of gases from water should be called "one degree." The apparatus used for collecting the gases he called a voltameter.

249. The Copper Voltameter.—For ordinary use the copper voltameter * is a very convenient and fairly accurate current-measurer. The solution may be a strong solution of copper sulphate with a few drops of sulphuric acid. The electrodes should be carefully cleaned copperplates. Copper wires, thoroughly cleaned and coiled into spirals as suggested by Ryan,† will be found convenient. The amount of copper deposited by the current is determined by weighing the negative electrode before and after the experiment.

250. The Silver Voltameter.—For experiments of the highest accuracy, silver is the substance chosen, although its manipulation is somewhat difficult. A solution of silver nitrate is placed in a platinum bowl which forms the negative electrode, while the other electrode is a strip of pure silver wrapped in filter-paper and suspended in the middle of the bowl. The method is not adapted for strong currents, and requires expensive apparatus. Its accuracy is so great, however, that it has been adopted as the standard for the legal definition of current strength by the United States and some other countries.‡ (See p. 166.)

251. Comparison of Voltameter and Galvanometer.—As compared with the use of galvanometers, the great advantage of the electrolytic measurement of currents is that they are not dependent upon the determination of the magnetic intensity of the earth, and they do not require a carefully measured standard galvanometer. Any galvanometer or

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* Directions for the use of this will be found in Gray's "Absolute Measurements in Electricity and Magnetism," p. 169.

† See Nichols' "Laboratory Manual of Physics," vol. I. p. 166.

‡ The practical details for obtaining a satisfactory deposit of silver are given in Gray's "Absolute Measurements in Electricity and Magnetism." p. 163.

ammeter may be used to measure currents if the value of its readings is determined by electrolysis. For this purpose the same current is to be passed through the voltameter and the galvanometer to be standardized.

For instance, suppose we have a galvanometer constructed like the absolute tangent galvanometer, p. 134, but are ignorant of the number or diameter of the windings or of the earth's intensity; pass a current through the instrument sufficient to give a deflection of about 45°. Connect a voltameter in series so that the same current shall flow through it. Then (p. 181)

$$W = eit, \quad \text{or} \quad i = \frac{W}{et}.$$

The same current as measured by the galvanometer is

$$i = \frac{r\mathcal{H}}{2\pi n} \tan \delta,$$

or, writing $G = \frac{2\pi n}{r}$,

$$i = \frac{\mathcal{H}}{G} \tan \delta,$$

where $\frac{\mathcal{H}}{G}$ is unknown.

Equate the two expressions for the current, and

$$\frac{\mathcal{H}}{G} \tan \delta = \frac{W}{et},$$

$$\frac{\mathcal{H}}{G} = \frac{W}{et \tan \delta},$$

in which all the quantities on the right side of the equation are known. Having calculated from this the value of $\frac{\mathcal{H}}{G}$, we thereafter have only to multiply the tangent of the deflection of the needle by this value of $\frac{\mathcal{H}}{G}$ in order to know the current passing through the instrument.

252. Electrolytic Meters.—Edison has devised an electric meter to measure the amount of current furnished to any house for lighting, etc., which is based upon electrolysis. A definite fraction of the whole current passes through a solution of zinc sulphate, and the amount of zinc thus deposited (determined by weighing the electrode from time to time) serves as a measure of the whole current.

253. To Detect Currents.—Electrolysis may be made to show the presence of even a feeble current. If a paper is moistened with a dilute solution of potassium iodide in which is some boiled starch, the passage of a current through the paper will be shown by the decomposition of the iodide, the liberated iodine forming with the starch a dark purple stain. This fact is utilized in some forms of telegraph to record electric signals which are sent over the wire. The current required to make the record is much stronger than is detected by delicate galvanometers, or even by the siphon recorder used in submarine telegraphy.

254. Electroplating.—It is evident that electrolysis is admirably adapted to the purpose of applying thin coatings of metals if a practical method of operating can be devised. This has been accomplished by the assiduous labors of Jacobi in St. Petersburg, Spencer in Liverpool, and many later workers, and now the electrical processes are universally employed.

255. Gold and Silver.—For electrogilding, a bath of gold chloride and potassium cyanide is prepared and the articles to be gilded are suspended in the bath and connected with the negative pole of a battery (wherever work is done on a large scale, dynamo currents are employed). A plate of gold forms the positive electrode, and is dissolved fast enough to replace the gold which is removed from the solution.

Silver is applied in the same way, a double cyanide of silver and potassium being used.

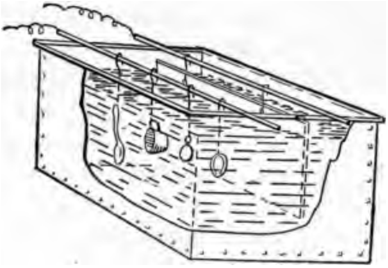

FIG. 105.—ARRANGEMENT OF BATH FOR ELECTROPLATING.

256. Nickel.—Nickel-plating has become very prominent of late years, as the metal forms a handsome and brilliant coating of great hardness which does not tarnish. The bath for nickel-plating is commonly a sulphate of nickel and ammonia.

In all electroplating the nature of the coating depends upon the strength and temperature of the solution and the current used. It is sometimes difficult to make an adherent deposit, and it may be necessary to first apply a layer of copper, which is more easily deposited in good condition. This is done when nickel is to be deposited on iron.

257. Copper.—Copper is also used for plating iron, either to improve its appearance or to protect it from rusting, being sometimes applied to objects as large as lamp-posts and columns. The first layer must be deposited from a solution that will not attack the iron, as the cyanide; the process may then be continued in a copper-sulphate solution till the desired thickness is reached.

Other metals are occasionally deposited. The face of a copper-plate engraving is sometimes protected by a thin film of iron ("steeling") which is deposited in a very hard condition and which wears much better than the copper itself.

258. Electrotyping.—A more usual way to protect engraved plates, and especially woodcuts, is to make copies of them to print from, reserving the originals for reproducing these copies. To accomplish this the face of the plate is covered with fine graphite, which is a good conductor but which will prevent the deposit from adhering. Copper is now deposited in a thick layer. This layer is removed and serves as a mold upon which a second deposit is made in the same way. This second layer is backed by a suitable thickness of type-metal, and is used for making the impressions. The mold is sometimes made by squeezing gutta percha upon the original plate and depositing the copper upon this. In either case the copper deposit reproduces every detail of the mold.

In a quite similar way it is not difficult to make copies of nearly anything. Medals, repoussée work, vases, statues, etc., may be copied in copper, silver, or gold.

259. Copper-refining.—The ease with which copper may be deposited from its salts, and the purity of the deposit thus obtained, have led to the extensive use of electrolysis for the purpose of refining the impure metal. Not only is copper thus obtained in a condition of great purity from inferior ores, but in many cases the gold and silver recovered from the metal in the process may nearly or quite repay the expense of refining. Many tons are daily treated by this method.

260. Chemical Processes.—Nor is electrolysis used for depositing metals alone. It is found to be possible to decompose solutions of common salt, and obtain chlorine and caustic soda on a large scale. The chlorine is used for the manufacture of bleaching compounds, and the soda is valuable for glass-making and many other purposes.

Sea-water when electrolyzed gives rise to unstable chlorine compounds, which prove of value in oxidizing the impurities of drinking-water, destroying the disease-germs.

Sewage treated by the current rapidly deposits the impurities and is rendered harmless. Lead may be dissolved under the action of the current and converted into "white lead" of excellent quality.

The chemical effect of the current opens a most attractive field for invention, and new uses are continually being found for its application.

CHAPTER XIX.

PHYSIOLOGICAL EFFECT OF CURRENTS.

261. Currents Affect the Nerves.—The discovery of the Leyden jar was due to the impression made by the discharge on the nerves of the experimenters. Galvani's valuable discovery also was due to the effect produced upon the nerves of a frog when a current passed through it. Older than Galvani's discovery was the observation that if a piece of lead and a piece of silver were touched together and so placed that both should touch the tongue, a peculiar taste would be noticed, which may be readily identified now as the same as that produced by putting the two poles of a voltaic cell to the tongue. In a similar way, if a current is passed through the ball of the eye, a sensation of light is perceived, which may be white or colored, depending on the strength of the current and on the observer. Sensations of sound and of smell may be produced in a corresponding way.

262. Muscular Contraction. — A muscular contraction, like that observed by Galvani in the frog's leg, takes place also in the body of a live animal. If handles attached to the poles of an induction-coil, or of a medical "magneto" machine, are held in the hands, and the current allowed to pass, it will be found that the mind has lost control of the muscles, which will be strongly contracted.

It is known to physiologists that, when volitions are sent from the brain along the nerve-fibres to the muscles, these nerve-impulses are accompanied by electric currents; but whether the current is the medium used by the brain to send its signals, or what is the exact connection between the current and the nerve-impulse, is not known.

263. The Current may Cause Unconsciousness and Death.—The numerous accidents from high-pressure circuits call emphatic attention to the danger of such currents to human life. It seems that the effect depends only on the current actually passing through the body, and that the current need not be very large to produce death. But the resistance of the body is so great that a high voltage is required to send even a feeble current through the body. This resistance depends very much on the condition of the skin, which when dry is a good non-conductor, but the resistance from hand to hand may be anything from several thousand to 200 ohms, and as a pressure of 2000 volts is quite certainly fatal it seems very certain that 3 or 4 amperes is a fatal current—probably much less than this would prove so. The discharge from a battery of Leyden jars may easily be fatal. Franklin relates,* with evident enjoyment, an experiment in which by such a discharge he knocked down six men standing in a row, who fell without feeling the shock. Since the discharge of a Leyden jar is of very short duration, it is quite possible that the instantaneous current in this case is abundantly strong enough to cause death without ascribing any other properties to it than are possessed by ordinary currents.

Death or unconsciousness from an electric current is produced without any sensation or consciousness of pain, provided the current through the body is sufficiently strong, probably because the nerve-centres lose their power of feeling before the sensation of pain reaches them.

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* Sparks' Life of Franklin, vol. v. p. 352.

CHAPTER XX.

MAGNETIC EFFECT OF THE CURRENT.

264. Early Experiments.—The experiments of Oersted showed that the electric current exerted a magnetic force. Arago, Ampère, Davy, and others soon found that this force would magnetize iron and steel. Arago * dipped the wire carrying the current into iron-filings and found that they clung to it while the current was flowing, but dropped off when the current stopped. Davy † attached short iron and steel wires at right angles to a wire, and on passing a current through the wire found the iron to be temporarily, and the steel permanently, magnetized. The effect was increased by winding the wire about the iron.

265. Electromagnets.—If a wire is coiled 50 or 100 times about a paper or glass tube and a current passed through it, it will attract and repel the poles of a magnetic needle, like a weak magnet. A bar of steel placed inside the coil will become permanently magnetized. A soft iron bar placed in the coil is strongly magnetic while the current passes, but loses much of its magnetism when it stops. A bar of soft iron thus magnetized by a current is called an electromagnet. Such magnets are of frequent use because of their great power and because they are under perfect control, acquiring, losing, or reversing their polarity as the current is started, stopped, or reversed.

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* Annales de Chim. et de Phys. [2], vol. xv. p. 93. 1820.

† Phil. Trans. 1821, p. 10.

266. Laws of the Electromagnet.—To determine which end will be a north pole, use the corkscrew rule on p. 128. The end out of which the lines of force come, by this rule, is the north pole of the magnet. If one faces the north pole of the magnet, the current will be found to flow around it in a direction opposite the motion of the hands of a clock.

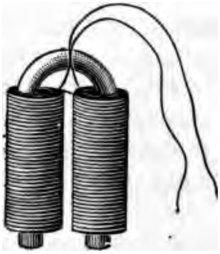
FIG. 106.—A HORSESHOE ELECTROMAGNET.

The strength of an electromagnet may be increased by increasing the number of turns and keeping the current constant, or by keeping the turns the same and increasing the current. In fact the magnetizing force depends only on the product of the current strength by the number of turns, and is therefore commonly reckoned in "ampere-turns." The ampere-turns on any magnet are calculated by multiplying the number of turns by the amperes flowing in the wire.

It must not be thought that the strength of the magnet is at all proportional to the number of ampere-turns on it.

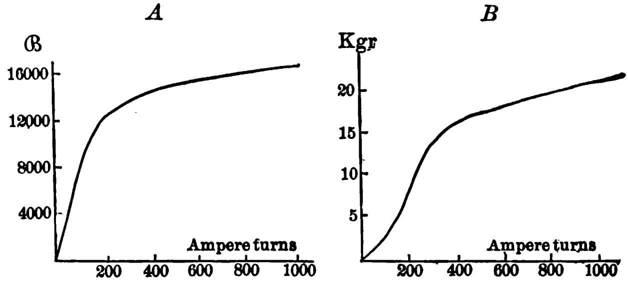

FIG. 107.

If we measure the strength of the magnet by the number of lines of force coming from its poles, the connection with the ampere-turns is given in Fig. 107, *A*; while if we measure it by the load it will carry, Fig. 107, *B*, gives the relation for a particular magnet. In each case the strength increases less rapidly as the magnetizing force becomes great, which is generally expressed by saying that the iron approaches saturation.

267. Force Inside the Magnet.—The lines of force referred to in Fig. 107 are those running from the magnet to its armature, and a method of measuring the strength of a magnetic field is given on page 98. But to form a conception of the state of things inside of the magnet is very different; and before we can do so at all we must imagine a little cavity to be made inside of which we may carry on our experiments.

However, in making a cavity or crevice for introducing a needle, we may change the state of things, no matter how small an opening we make. To show this, consider two cases.

268. First Case.—Let a steel magnet be bored lengthwise so as to have a small hole extending from one end to the other, Fig. 108. Outside of the magnet and also through the hole lines of force run from the north to the south pole, and if a small compass is carried along the hole from the north to the south end, it will point steadily toward the south end of the magnet until the north pole is passed, when it will suddenly turn around and point in the opposite direction.

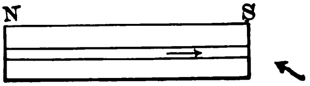

FIG. 108.

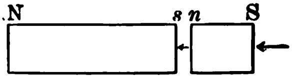

FIG. 109.

269. Second Case.—Suppose the magnet to be divided by a narrow crack, right across the magnet, into two parts,

Fig. 109. As found in case of the broken magnet, p. 81, two new poles will appear; and if a small compass is now introduced into this crack, it will point toward the north pole of the bar—the force is in a direction opposite to what it was before.

In this second case, suppose the crack and the compass could move slowly toward the right, the material of the bar gradually disappearing from the right side and reappearing on the left. (This might perhaps take place if the magnet were liquid and the crack did not extend quite across.) It is fairly evident that no change in the direction or condition of the compass will take place unless it comes when we get near to the end and are just taking off the last layer of the magnet from the right side of the crack. But even then the pole *n* has approached very near to the pole *S*, so that they have begun to neutralize each other, and just before the last film is removed *n* and *S* have quite neutralized each other, and no change at all takes place when the last layer is removed.* Therefore the force in a cavity of this kind inside a magnet is quite continuous with the force outside in both amount and direction; while in the first case the direction of the force (in a permanent magnet) suddenly changes in direction as the pole is passed.

270. Magnetic Force and Magnetic Induction. — The force on a unit pole at the centre of a minute cylindrical cavity whose length is much greater than its diameter and whose axis is in the direction of the magnetization is called Magnetic Force, and I shall always designate it by the letter $\mathcal{H}$.

The force on a unit pole at the centre of a minute disk-

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* The reasoning here is far from strict. The comparison of cases 1 and 2 shows that the removal of even a very minute portion of the magnet may make a very great difference. The strict proof of the statements here made will be found in Maxwell's Electricity and Magnetism, part III. chap. II.

shaped cavity whose diameter is large compared with its thickness and which is at right angles to the magnetization is called Magnetic Induction. I shall always designate it by the letter $\mathcal{B}$.

271. Induced Magnetism.—These quantities, magnetic force and magnetic induction, are of special importance when dealing with electromagnets, or other induced magnets, as a bar of iron between the poles of a magnet. In such cases as this $\mathcal{B}$ and $\mathcal{H}$ are usually in the same direction, because the field due to the magnet or magnetizing coil is more powerful than the effect of the poles of the iron. $\mathcal{B}$ is however greater than $\mathcal{H}$ because if the compass is carried along the tubular cavity as before, when it gets to the end of the iron, the pole which, inside the magnet, opposed the inducing effect of the coil now aids it, and the value of $\mathcal{H}$ outside of the iron is therefore greater than inside. But $\mathcal{B}$ is the same inside as outside in both strength and direction. Outside of the iron $\mathcal{B}$ and $\mathcal{H}$ are the same thing; it is only inside of it that we can distinguish between them; therefore it is plain that inside of the magnet $\mathcal{B}$ exceeds $\mathcal{H}$ by an amount which depends on the amount of induced magnetism.

272. Value of the Magnetic Induction.—In Part III, Chap. II, of his treatise, Maxwell shows that

$$\mathcal{B} = \mathcal{H} + 4\pi\mathcal{I},$$

and the reason for the equation may be readily seen.

For if a current passes through the wire of a long solenoid (Fig. 110), $\mathcal{H}$ lines of force per square centimeter

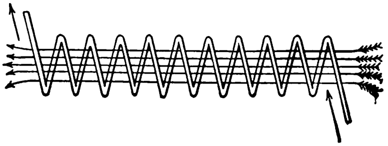

FIG. 110.

emerge from the end. Place a bar of iron in the coil and call $\mathfrak{B}$ the number per square centimeter now emerging. We saw (p. 89) that 4π lines of force emerge from a unit pole, and if the intensity of magnetization be $\mathfrak{I}$, then $4\pi\mathfrak{I}$ emerge from each square centimeter of the pole. The iron therefore adds $4\pi\mathfrak{I}$ lines of force, and the $\mathfrak{B}$ is made up of $\mathfrak{H}$ and $4\pi\mathfrak{I}$ added together.

273. Ohm's Law Applied to Lines of Induction.—The calculation of the number of lines of force of an electromagnet is a very important operation. In doing this it is customary to use an analogy with Ohm's law, and to consider that the current exerts a certain force tending to set up lines of induction. This magnetizing force has to overcome a certain magnetic resistance (called "reluctance"), and the whole number of lines of induction (as in Ohm's law for electric currents) is equal to the total magnetizing force divided by the magnetic resistance of the circuit.

274. Permeability.—Conductivity for lines of induction is known as "permeability." It is measured by the ratio of the magnetic induction to the magnetic force, and is designated by the letter μ.

$$\mu = \frac{\mathfrak{B}}{\mathfrak{H}}.$$

The laws of magnetic circuits are much more complicated than for electric circuits. The reluctance of the iron depends not only upon the quality of the iron, but as well on the number of lines of induction passing through it; and the matter is further complicated by the fact that the lines spread out and pass through the air in ways difficult to predict, thus occupying a path of indefinite cross-section.

The shape of an ordinary electromagnet is also much more irregular than that of the simple wires used for electric currents.

For these reasons the calculations are only approximate, yet they are of great service in designing apparatus and machinery employing electromagnets.

275. Illustration. — An illustration will serve to give more definiteness to these statements. When a current flows through the wires of an electromagnet, Fig. 111, it exerts a certain magnetizing force, and the number of lines of force resulting depends upon the quality of the iron and the position of the armature. With the armature altogether removed the lines will be arranged about as shown in Fig. 111, *A*. As the armature is placed near the magnet but not touching, Fig. 111, *B*, shows the arrangement; while if the armature is placed against the poles, they will extend as shown in Fig. 111, *C*. Iron is a much better conductor of the lines than air, and the path in air is much shortened by bringing the armature up, so that more lines are set up in this case, and of these many more go through the iron—fewer going around through the air; so that for both reasons the attraction of the magnet for the armature is much greater at short than at long distances. We are not able, however, to apply the law of inverse squares, and indeed

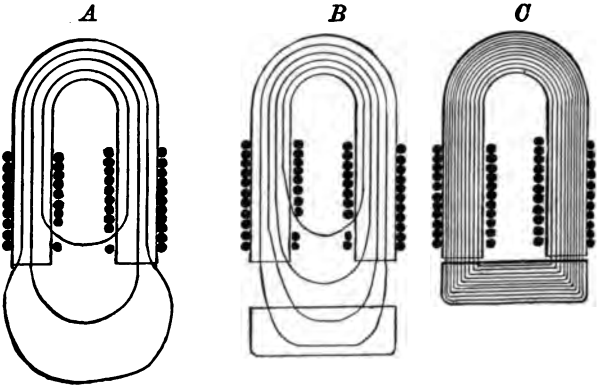

FIG. 111.

there are comparatively few places in practice where it can be satisfactorily applied.*

276. Value of the Magnetic Permeability.—In order to calculate the number of lines of induction from the dimensions of the magnet we must know the permeability of the iron. This varies with the induction. The following tables contain the value of the permeability of two samples of iron, tested by Hopkinson,† for different values of $\mathfrak{B}$:

Wrought Iron.		Soft Cast Iron.	
$\mathfrak{B}$	μ	$\mathfrak{B}$	μ
5000	3000	4000	800
9000	2250	5000	500
10000	2000	6000	279
12000	1410	7000	133
14000	823	8000	100
16000	320	9000	71
18000	90	10000	53
20000	30	11000	37

277. Calculation of Magnetic Reluctance.—As in electric circuits we may calculate the reluctance of the magnetic circuit for the case shown in Fig. 111, *C*, as follows:

Let μ_1, l_1, and s_1 be the permeability, length, and cross-section of the magnet, and μ_2, l_2, and s_2 the corresponding quantities for the armature; then the reluctance will be

$$\frac{l_1}{\mu_1 s_1} + \frac{l_2}{\mu_2 s_2}.$$

To this must be added a certain quantity for the resistance of the joints, which cannot be made to entirely disappear.

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* For an interesting discussion of this whole subject see S. P. Thompson's "Electromagnets," from which these figures are taken.

† Hopkinson gives the result of a large number of tests in Phil. Trans. 1885.

For the second case, Fig. 111, *B*, the air-resistance becomes more important than that of the iron, and if the armature is at any considerable distance from the magnet, the irregular path of the lines of induction makes it impossible to assign any value to *s*. Hence the calculation must be based on empirical data, or only roughly approximated.

278. Attractive Force of Magnets.—Theory and experiment both show* that if $\mathfrak{B}$ lines of induction per square centimeter run from a magnet to its armature, and if the pole area is *A*, then the attractive force is

$$P = \frac{A(\mathfrak{B}^2 - \mathfrak{H}^2)}{8\pi}.$$

This formula may be used for calculating $\mathfrak{B}$ from the load sustained by the magnet. $\mathfrak{H}$ may generally be neglected in comparison with $\mathfrak{B}$. (In this formula *A* is to be measured in square centimeters, and *P* in dynes.)

It is because the attractive power depends upon $\mathfrak{B}^2$ that this power increases more rapidly than the value of $\mathfrak{B}$, as shown in Fig. 107, *A* and *B*.

Since an electromagnet may be made to carry about 115,000 lines per square inch, it follows that it would sustain a pull of about 90,000,000 dynes or 200 lbs. weight for each square inch of pole-surface.

279. Ascending and Descending Curves of Magnetization.—The curve Fig. 107, *A*, gives an average value for the induction in an iron magnet with different magnetizing forces, but more careful examination shows important modifications. Suppose that a very long, thin bar of iron is placed in a long helix through which a current may be made to pass. If the bar has never been magnetized, its magnetization for increasing values of $\mathfrak{H}$ will be as shown by the line *OA*, Fig. 112, beginning at zero and increasing

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* Ewing. Magnetism of Iron, p. 245.

at first more rapidly, afterwards less rapidly than the magnetizing force. Suppose that the magnetization has been carried to the point A, and then the current in the coil is gradually reduced. The magnetization will much of it be permanent, so that there will be comparatively little falling off even when the current has fallen to the value zero, as indicated at the point E. The line OE represents the permanent magnetism in the bar and is called its "retentivity." Now let the current be gradually started in the opposite direction. If the specimen is soft iron, it will require but a small current to completely demagnetize the bar, as shown at C. The line OC measures the "coercive force" of the material, and in soft iron is comparatively small even though the retentivity may be large—larger even than in steel. On increasing the strength of the reverse current, the iron is again magnetized in the corresponding direction, and by gradual changes in the direction and strength of the current, the operation indicated by the curve $AECA'DB$ may be repeated as often as desired. The area of the curve has a most important bearing on the

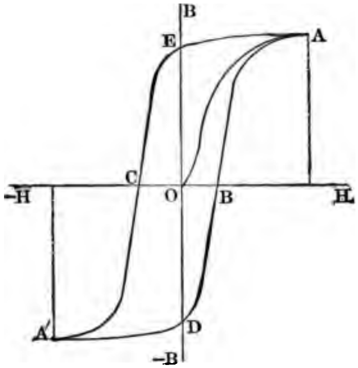

FIG. 112.

application of the material to alternate-current apparatus, as will be explained in describing such apparatus.

280. Ampere's Theory of Magnetism.—All these phenomena point to the rotary nature of magnetism. The connection between a current flowing in a circular coil of wire and a magnet cannot be accidental. Ampere was led by his experiments upon electric currents to propound the remarkable theory that there were currents actually flowing in a steel or iron bar. Not, of course, about the bar as a whole, as they flow about an electromagnet. Since each particle of steel is a magnet, each particle must contain a current. Ampere's theory is that each molecule of iron has an electric current flowing about it. These currents are present in ordinary iron, but pointing in every possible direction. The process of magnetization consists in so arranging these current that they are more or less in the same direction.

281. One Difficulty.—Of course such a theory will account for the similarity between magnets and currents, but why do not the currents stop—what keeps them going? An electric current in a copper wire heats the wire and almost immediately comes to rest if the force which produced it is removed. And the currents flowing about the molecules of iron must soon cease to flow if the current meets with any resistance. In a perfect conductor the flow would never stop, as a moving body never stops unless there is some opposition to its motion; but one hesitates to allow the possibility of perfect conductivity in an atom or molecule when there is no approach to such perfection in any substance upon which we are able to experiment.

282. Atoms are Perfectly Elastic.—Further thought may somewhat lessen the force of this objection when we consider some of the other properties of atoms. If an ivory ball is dropped upon a plate of glass, it bounds up a few times and soon comes to rest. Though fairly elastic, its motion soon disappears, being converted into heat. And so all bodies when they strike together show an imperfect elasticity; part of their motion is retained, part goes to set the molecules in motion—in other words, is converted into heat. But when two atoms clash together we cannot suppose any such imperfect elasticity. They must separate after collision with as much energy as they had before collision, for there is no other form into which their energy can be changed. It is easier to believe that atoms are perfectly elastic than to believe that the law of conservation of energy is not true.

Similarly, it is not at all impossible that while the passing of electricity from one atom to another shakes them up and converts the energy into heat, it may still flow in a circuit about the individual atom without friction. We cannot say that it does so; it simply seems possible. And if the current about the atoms meets with no resistance, it can no more stop than can the stars in their orbits.

On the other hand, it must be confessed that no direct evidence of existence of these currents has been found. Ewing has attempted to weaken them by placing the iron in very strong magnetic fields—which would tend to stop currents flowing in a coil of wire, but without effect.

283. Weber and Maxwell. Ewing.—Ampere's theory attempts to account for the magnetic condition of the particles of iron Weber, Maxwell [*] and others have successively added to it by assuming different kinds of friction between the molecules in order to explain the peculiar connection between the magnetizing force and the magnetization produced, shown in Fig. 107, p. 193.

The most promising attempt to reconcile the various difficulties is that of Ewing,[†] who thinks that the molecular

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[*] Maxwell's "Electricity and Magnetism," part III. chap. vi.

[†] *Phil. Mag.*, Sept. 1890. See also Ewing's "Magnetic Induction in Iron," § 171, etc.

magnets are not held in place by frictional forces, but by their mutual attraction as magnets, which causes the poles to point every way till some outside magnetic force brings them into a common direction.

The mathematical discussion of this theory has not yet been attempted, but by constructing a great many little magnets, arranging them on a board and observing the effect of magnetizing forces on them, Ewing found that such a system of magnets would imitate an actual magnet in nearly all respects.

CHAPTER XXI.

MAGNETISM AND LIGHT.

284. Correlation of Forces.—One of Faraday's researches in which electromagnets were employed is of special importance in showing the connection between electricity and light.

To the mind of Faraday the unity of nature was no mere abstraction. The law of conservation of energy, linking the various physical forces in close connection, had not yet been thoroughly developed by Joule; yet Faraday said:* "I have long held an opinion, almost amounting to conviction, in common I believe with many other lovers of natural knowledge, that the various forms under which the forces of matter are made manifest have one common origin; or, in other words, are so directly related and mutually dependent that they are convertible, as it were, one into another, and possess equivalents of power in their action. . . . This strong persuasion extended to the powers of light, and led, on a former occasion, to many exertions, having for their object the discovery of the direct relation of light and electricity, . . . but the results were negative. . . . These ineffectual exertions and many others which were never published could not remove my strong persuasion, derived from philosophical considerations; and therefore I recently resumed the inquiry by experiment in a most strict

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* Exp. Res., vol. III. p. 1.

and searching manner, and have at last succeeded in magnetizing and electrifying a ray of light. . . ."

285. Faraday's Experiment.—The experiment to which he here refers is as follows:

A powerful electromagnet has its poles bored through, so as to allow the passage of a beam of light. A Nicols prism is placed at one end of each hole, and these are turned so that no light passes. The light passing through the first prism is said to be "polarized," i.e., all its vibrations are in one direction. The second prism, or "analyzer," allows only the light whose vibrations are in one particular plane to pass through, and if turned properly will intercept all the light from the first prism.*

Now if turpentine, solution of sugar, quartz crystal, or various other substances are placed between the poles, and in the path of the light, the plane of the vibration is rotated so that there is a greater or less component of the vibration in the proper direction to pass through the second prism. Therefore more or less light can be seen to come through the analyzer, but this may be extinguished by rotating the analyzer.

286. The Magnetic Rotation of Light.—In Faraday's experiment a piece of heavy glass was placed between the poles of the magnet. This glass has not the power of rotating light, but when the current passes through the coils of the magnet the light becomes visible. The lines of force thus confer upon the glass the power of rotating the direction of the vibration.

There is a remarkable difference, however, between the rotation produced by turpentine and that produced by the lines of force. In the former substance (and in all substances which rotate the ray when not magnetized) a beam of light

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* For further statements about polarized light the reader is referred to any text-book on Light, as Glazebrook's "Physical Optics."

reflected back through the liquid is rotated back again and can pass through the prism by which it entered. In the case of magnetic rotation, if the light is reflected back through the glass, the rotation is doubled; each time the beam travels through the glass it is rotated in the same direction and by the same amount. The direction of the rotation is reversed if the current is reversed.

287. Magnetic Rotation Indicates a Motion in the Medium.—A rotation like that of turpentine can be explained by the structure and elastic properties of the substance; the magnetic rotation can be explained only by asserting that there is a rotation actually going on in the glass.

We thus learn—

1st. That the lines of force have a rotating property or power.

2d. That the medium which is rotating is concerned in the propagation of light. We also know that a whirling or circular current of electricity is a magnet and has lines of force. It would perhaps be hasty to assert from these facts that a line of force is a whirl in the luminiferous ether. The rotation of light vibrations is different in amount and even in direction in different substances, and in a vacuum which readily conducts lines of force no rotation has ever been observed; it seems quite safe to say, however, that magnetism is a property of electricity in rotation, and that lines of force are associated with a rotation of the luminiferous ether.

The inference that the ether is the same thing as electricity is obvious, and many other facts point in the same direction. They certainly are intimately related if not indeed identical. In the present state of our knowledge it is difficult—impossible—to distinguish between them; but we are hardly able as yet to assert their complete identity.

288. Amount of Rotation.—Verdet and other experimenters have made measurements of the amount of rotation produced in a magnetic field. The following laws have been discovered:

1st. The amount of rotation is proportional to the strength of the field.

2d. It is proportional to the distance that the ray travels in the direction of the field. There is also a certain connection between the index of refraction and the rotating power for substances of the same chemical nature.

In a field of 10,000 C. G. S. units the amount of rotation experienced by a ray for each centimeter that it travels in the direction of the field is as follows:

ROTATION OF YELLOW (Na) LIGHT PER CENTIMETER IN A FIELD WHOSE INTENSITY IS 10,000.

Substance.	Rotation.
Carbon bisulphide	7°.004
Rock salt	5°.903
Air	0°.0022

289. Rotation by Iron.—Iron is not ordinarily reckoned as a transparent substance, but the experiments of Kerr* show that a ray of polarized light when falling upon the polished pole of an electromagnet experiences a rotation, indicating that the light penetrates slightly into the iron and during this very short period while it is penetrating the iron and coming out again an appreciable amount of rotation is experienced. Kundt has found the rotating power of iron to be more than 30,000 times that of glass in the same field.

290. Hall Effect.—The following discovery by Hall has been shown to be closely connected with the magnetic rotation of light. A cross-shaped piece of gold-leaf, *abcd*, Fig.

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* *Phil.Mag.*, May 1877 and March 1878.

113, is placed on a piece of glass. A current can be made to enter at *a* and leave the strip at *b*. When this takes place, the pressure at the point *c* is the same as at *d*, as shown by a potential galvanometer *E* connected to these points. The strip is now placed between the poles of an electromagnet so that the lines of force pass perpendicular to the sheet of gold. On magnetizing the magnet, the points *c* and *d* are no longer at the same potential. The equipotential lines have become shifted or rotated, as shown to an exaggerated degree in Fig. 113, *B*. This rotation of the equipotential lines is identical in nature with the rotation of polarized light, and has been proved * to be sufficient in amount to account for that rotation.

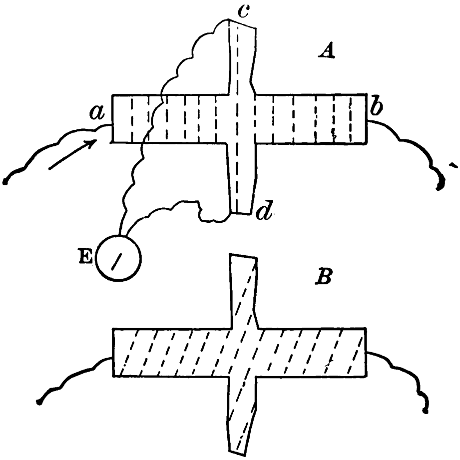

FIG. 113.

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* Rowland in *Phil. Mag.*, June 1880, which also contains Hall's paper.

CHAPTER XXII.

THE MAGNETIC TELEGRAPH.

291. Sturgeon and Henry.—Early experimenters in electricity suggested its use for the transmission of signals. Each newly discovered property was in turn applied to this end. The magnetic telegraph of the present day is based upon the use of Sturgeon's electromagnet. The modification of this apparatus by Henry,* who used many turns of insulated † wire, in place of the few turns used by Sturgeon, made it possible to employ the force of the electromagnet at a distance. In 1831, Henry made use of the electromagnet to ring a bell at the other end of his room through a wire more than a mile long. ‡

292. Morse.—Morse had been for some time working on the same problem when in 1836 he became acquainted with this improvement, and, with his assistants, brought out the system which has come into general use. His first line was built from Baltimore to Washington in 1844.

Wheatstone, in England, built a line one or two miles long in 1837 which required six wires, and Steinheil, in Germany, described one at about the same time which would require but two. At this date Morse's line was in operation only in his laboratory.

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* Scientific Writings of Joseph Henry, vol. I. p. 37.

† Henry, Faraday, and other early experimenters insulated their own wire by wrapping it with strips of cloth.

‡ *L. c.* vol. II. p. 426.

293. The Morse Telegraph.—As at present employed in the United States, the Morse system employs three instruments at each station, the key, the relay, and the sounder.

The key, Fig. 114, is a metal bar which is hung on an axis at the middle and which can be pressed down by a knob at one end. When released it is raised by a spring. This key is placed in the line as shown in the diagram Fig. 117, one end of the line connecting with the axis, while the other end is connected with a point beneath the bar so that when the key is pressed down by the operator the line is closed, while when it is raised the continuity is broken. When not in

FIG. 114.

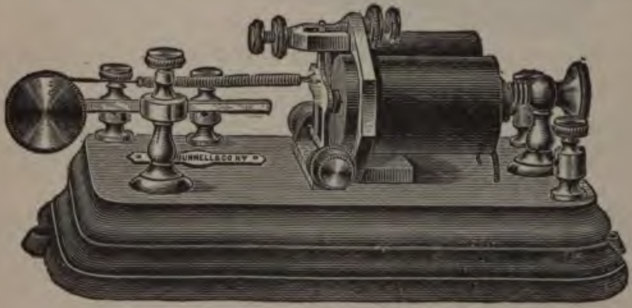

FIG. 115.—THE TELEGRAPH RELAY.

use the key is cut out by a small arm at the side which closes the circuit.

The relay, Fig. 115, consists of a horseshoe electromagnet in front of whose poles is a bar of soft iron. This bar is attached to a vertical arm which is pivoted at its lower end, and is drawn back from the poles by a light spring. The coils of the magnet are placed directly in series with the main line, so that a current over the line excites the magnet and attracts the soft iron bar (or "armature"). When a key on the main line is open the current ceases and the spring draws the armature back.

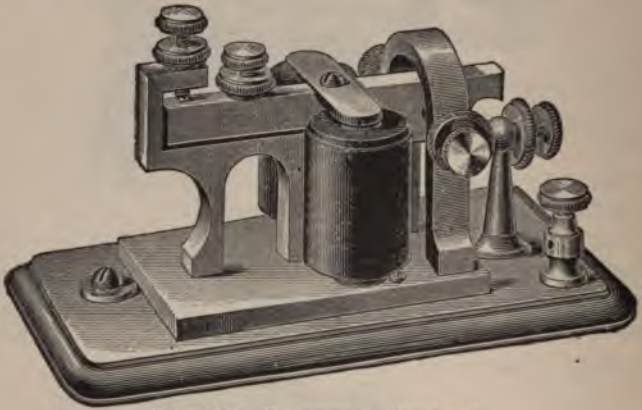

FIG. 116.—TELEGRAPH SOUNDER.

294. Arrangement of Line.—The arrangement of these instruments is shown in the diagram Fig. 117. Each station along the line is provided with a key and relay, while at one or both ends is placed the main battery. A wire forms one conductor between the poles of the battery, while the earth ordinarily forms the other; connection being made at each end by plates of copper buried in the ground.

Suppose now that an operator wishes to send a message. He opens his key. Every armature along the line flies back. By pressing down his key at certain intervals he produces corresponding clicks in all the instruments, and by a suitable combination of such clicks calls the attention of the operator who is to receive the message. The message itself consists of a series of contacts of the key and corresponding clicks in the instruments, which stand for letters of the alphabet.

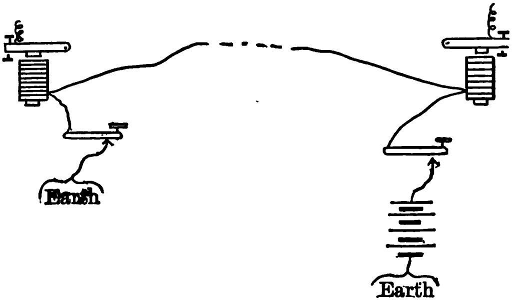

FIG. 117.—DIAGRAM OF LINE.

295. Messages are Read by Ear.—In the earlier forms of receiving instruments a mechanism was provided by means of which the motions of the armature were recorded on a slip of paper which passed (by clockwork) in front of the armature. A momentary closing of the key made a dot on the paper, while a longer closing produced a dash. Hence the clicks are still known as dots and dashes, although this form of receiver has wholly gone out of use except in small country stations where the operators have not acquired the necessary skill to read by the sound of the instrument.*

I have described the process as if the relay were the instrument whose clicks were read by the receiving operator.

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* I write only of practice in this country. In some countries the recording receiver is still in use and many of the details are quite different.

On lines of ordinary length the current is quite weak and the indications of the relay are too faint to be readily distinguished; hence a " sounder " is used.

296. The Local Circuit.—The sounder, Fig. 116, looks like the relay, but is wound with coarser wire so that a small electromotive force may be able to send a fairly strong current through its coils. Certain connections and adjustments, used on the relay, are also unnecessary. This instrument is used as follows: Each station is provided with a local battery of two or three cells. One pole of this battery is connected to the armature of the relay. The other is carried to the sounder and through this to an insulated stop in the relay. When the main current attracts the armature of the relay, it is brought up against this stop and thus closes the local circuit, and the coils of the sounder are magnetized and its armature is thus attracted; it therefore repeats the signals given by the relay itself, but in a much louder tone. The relay thus acts as a key for the local circuit, while the signals are actually read from the sounder. These connections are shown in Fig. 118.

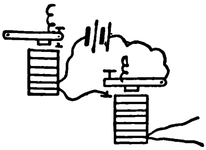

Fig. 118.

297. The Alphabet.—The Morse alphabet as used in this country is made up of a series of long and short clicks and spaces as indicated by the following table.

A	· —	H	· · · ·	O	· ·	V	· · · —
B	— · · ·	I	· ·	P	· · · · ·	W	· — —
C	· · ·	J	— · — ·	Q	· · — ·	X	· — · ·
D	— · ·	K	— · —	R	· · ·	Y	· · · ·
E	·	L	——	S	· · ·	Z	· · · ·
F	· — ·	M	— —	T	—		
G	— — ·	N	— ·	U	· · —		

The international code is different from this in not employing the long spaces in the letters, as in C, O, R, etc.

This involves other changes, and the alphabet is as follows. No letter in this alphabet contains more than four characters, and no long spaces are used.

A	·—	H	····	O	———	V	···—
B	—···	I	··	P	·——·	W	·——
C	—·—·	J	·———	Q	——·—	X	—··—
D	—··	K	—·—	R	·—·	Y	—·——
E	·	L	·—··	S	···	Z	——··
F	··—·	M	——	T	—		
G	——·	N	—·	U	··—		

298. The Duplex System.—Between large cities there is enough business to demand the constant employment of several lines. To enable one line to do as much business as possible, methods have been invented for sending messages at the same time in both directions. One of these systems utilizes the principle of Wheatstone's bridge. The connections are made as in Fig. 119, where *BB'* is the main line. When the key *K* is depressed the current divides, part going to the line and part to the ground. Resistance-coils are placed in *AB*, *AC*, and *EC*, and if these are properly adjusted, as in resistance measurements, there will be no current through the local relay *R*. Therefore any signal from one station will not affect the relay at the same station. When the current arrives at the other end of the line it again divides, part going through *R'*, which is thus able to receive the signal. The signal is received by the instrument *R'* whether the key *K'* is open or closed, though the distribution of current in the two cases is quite different.

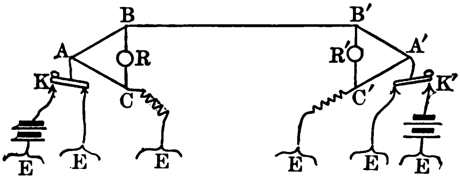

FIG. 119.

299. The Quadruplex.—A method of sending two messages in each direction over the same line is in use, and is known as the quadruplex system. Multiplex systems, in which a much larger number can be sent, have been invented, but have not yet come into extensive use.

It is not possible to send as many messages by one line with a quadruplex system as by four ordinary lines. The adjustments are more complicated and the speed of working is somewhat reduced. Still they are of decided advantage.

300. Time and Longitude.—The speed of transmission of telegraphic signals renders them extremely valuable for time purposes. The pendulum of a standard clock at some observatory can be made to act as a key in a telegraph line, and the ticking of the clock is thus reproduced in the armature of every instrument on the line. In this way railroads control the clocks at all the stations along their lines, and cities are furnished with standard time. By the comparison of local time with the time at Washington the longitude of all important points has been accurately determined.

301. Submarine Telegraphy.—The problems concerned in the telegraphic connection of Europe and America were of the gravest character. The difficulty of insulating a conducting wire, of laying a cable if it could be made, the marine surveys required, the electrical resistance, and the money involved—to all these was added the greater difficulty that the cable would act like a Leyden jar of which the conducting wire is the inner coating and the sheathing or the water outside is the outer coating. Consequently if the key at one end is closed, the current first flowing in serves only to charge the line, and the pressure at the other end rises but slowly, while the signals even then are much too feeble to affect a relay placed there.

The successful carrying out of the enterprise and the overcoming of all obstacles was accomplished by the indomitable energy and business enterprise of Cyrus W. Field and the scientific and mechanical skill of William Thomson.* The conductor, formed of copper wires, is surrounded by an insulating layer of gutta percha, and a protecting sheath of hemp and iron wires placed about the whole, as shown in section in Fig. 120. The signals were at first received by a mirror galvanometer designed for the purpose by Kelvin. The operator would follow with his eyes the movement of a spot of light reflected from the mirror. The "siphon recorder" has now replaced the mirror galvanometer on all the principal lines.

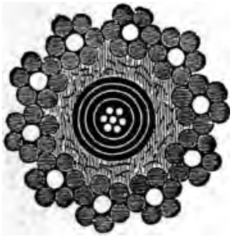

FIG. 120.—SECTION OF CABLE.

302. The Siphon Recorder.—This instrument, shown in Fig. 121, is simply a D'Arsonval galvanometer (see p. 138) specially adapted to this use. The moving coil carries a fine glass tube which acts as a siphon, one end dipping in a vessel of ink, while the other end distributes this ink in a wavy line over a ribbon of paper which is carried by clockwork past the end of the siphon. Thus as the coil and siphon is moved back and forth by the current through the coil, a record of the motion is made upon the paper (see Fig. 122). The tube of the siphon is so fine that ink flows through it only while it is touching the paper, and to prevent sticking it is constantly jarred, a vibrator being attached to the apparatus to accomplish this result. The Morse alphabet is used, deflections to one side standing for dots, those to the other side for dashes.

Cables now connect nearly all parts of the world. They

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* Knighted for this achievement in 1866; created Lord Kelvin in 1892.

have been successfully duplexed, and by their aid the difference of longitude of Washington, Greenwich, and Paris

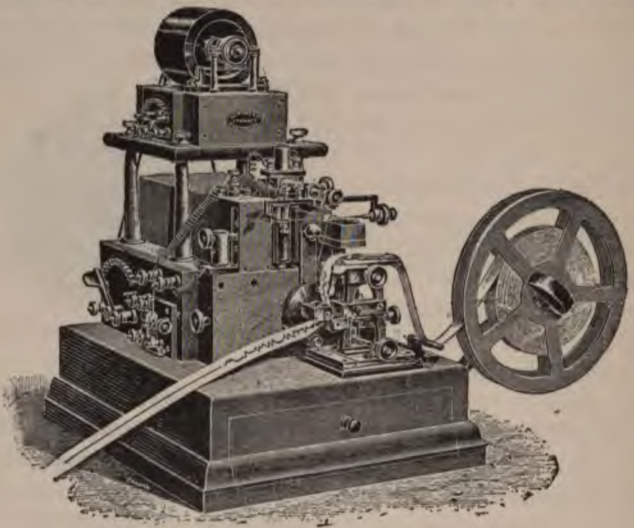

FIG. 121.—SIPHON RECORDER.

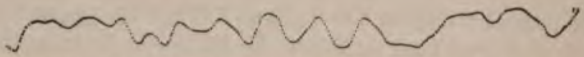

FIG. 122.—RECORD RECEIVED BY THE SIPHON RECORDER.

has been determined, thus connecting American and European surveys.

CHAPTER XXIII.

CURRENTS BY INDUCTION.

303. Induced Currents.—Closely connected with the subject of electromagnets must be placed Faraday's grand discovery of induced currents. In the series of remarkable experiments made by him on the connection between various physical forces he says: * "Whether Ampere's beautiful theory were adopted, or any other, or whether reservation were mentally made, still it appeared extraordinary that as every electric current was accompanied by a corresponding intensity of magnetic action at right angles to the current, good conductors of electricity, when placed within the sphere of this action, should not have any current induced through them, or some sensible effect produced equivalent in force to such a current."

As the medium about a magnet or a wire carrying a current is plainly in a different state from what would exist were the magnet or the current absent, there might naturally be some effect produced on a wire in this region.

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* Exp. Res., vol. I. p. 2. Read again in this connection the quotation on p. 205, and also the following, with which he concludes an unsuccessful series of experiments on the connection between gravitation and electricity: "Here end my trials for the present. The results are negative. They do not shake my strong feeling of the existence of a relation between gravity and electricity, though they give no proof that such a relation exists." (Exp. Res., vol. III. p. 168.)

Faraday's experiments on induced currents are described at length in Fleming's "Alternate Current Transformer," vol. I. p. 1.

304. Faraday's Experiment on the Mutual Induction of Two Circuits.—Faraday's search for such an effect, unsuccessful for seven years and several times abandoned,* was finally rewarded by the discovery of an induced current. He wound several layers of wire on a block of wood, each layer being a separate wire.

The first, third, fifth, etc., layers were connected so as to form one circuit, through which the current from a battery could be passed, while the alternate layers formed another circuit which was connected with a sensitive galvanometer. While a current is flowing through the one circuit no indication of a current in the other is shown by the galvanometer; but at the instant when the battery current starts, a momentary current is observed. At the instant when the battery current is stopped a similar momentary current is also noticed, but this time in the opposite direction. In either case the needle simply swings to one side, then swings back and forth, coming to rest in its original position.

305. The Motion of a Current Sets up a Current.—Again let two coils be wound, each containing fifty or seventy-five feet of wire, forming a ring of six inches in diameter. Let one be connected with a battery of two or three cells, and the other with a sensitive galvanometer. Now if one coil is brought quickly up to the other, a deflection of the galvanometer is noticed. On quickly taking it away, a deflection in the opposite direction is produced.

Carrying the current to a distance has the same effect as stopping the current; bringing it up is the same as starting one.

306. Induction by Magnets.—In place of the coil carrying the current, use a magnet. Putting the magnet quickly into the coil or pulling it out has the same effect as per-

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* See article "Faraday" in Enc. Brit., 9th ed.

forming the same operation with the current. The effect of the two poles is opposite—either pole just replaces a circuit through which a current flows so as to produce the same lines of force. Here, as everywhere else, the current and the magnet are identical in their operation.

307. Lines of Force and Induced Currents.—Comparing these experiments, we see that whenever lines of force cut across a wire they produce in it an electromotive force. Thus there are lines of force running from the north to the south end of a magnet, and others threading the circuit carrying a current. The motion of the magnet or coil therefore causes a motion of its lines of force, and when these are carried across a wire an induced current is set up. Again, when the current starts in a wire, lines of force, beginning as circles close to the wire, start up and swell out until they reach the place occupied when the current is steady. In so doing they necessarily cut across any wire in the region. When the current stops, the lines again collapse and cut the circuit in the opposite direction. When lines of force are cutting across different parts of the wire in different directions, their influence is opposed.

308. Some Illustrations.—This was clearly shown by many of Faraday's experiments. Thus a circuit may be arranged as shown at *ab*, near a magnet. Now if the magnet is rotated about its axis, its lines cut the wire in the region *a* and again in the region *b*, and the electromotive

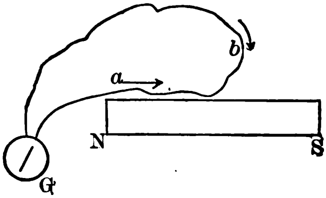

Fig. 123.

forces thus produced are equal and opposite and no current is set up in the wire. Again, let a conductor, *abcd*, Fig. 123, in a uniform field be moved about in any way so that its plane is always parallel to its present position, i.e., in any way which does not at all rotate the plane. Then whatever electromotive force may be developed by the motion in the region *ad* will be exactly neutralized by that developed in *bc*. Not so if the field is not uniform. In that case the wire at *bc* may be cutting across more lines than the portion *ad*, and thus an excess of electromotive force in one direction will exist. (See Fig. 127.) Or if the coil is rotated so that one side of it moves across the field while the other side is still or moving less rapidly, there will be an electromotive force and a current set up (Fig. 125).

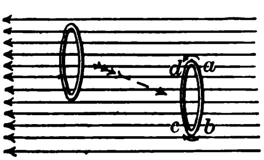

FIG. 124.

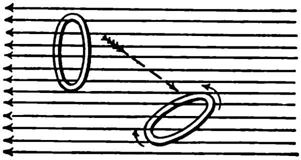

FIG. 125.

The easiest and most useful way to tell whether one part of the circuit cuts more lines of force than the other parts cut in the other direction, is to count up the total number embraced by the whole circuit at the beginning and again at the end of any moment, and if there has been any change in the number, there has been an electromotive force acting during that moment.

309. The First Law.—Hence we have the following law: Whenever there is a change in the total number of lines of force included in a circuit there is an electromotive force in that circuit.

310. The Value of the Electromotive Force.—The current produced on quickly moving a magnet up to a coil of wire deflects a galvanometer equally whether the motion is very rapid or only moderately so, and is the same in amount whether the magnet is carried off or brought back. If the magnet is withdrawn slowly, it is plain that the current lasts longer, so that it must be proportionately weaker; for when the galvanometer is thus used to measure momentary currents it measures, not the strength of the current at any instant, but the total flow of electricity (see p. 141); hence we may deduce the second law.

311. The Second Law.—The electromotive force is proportional to the rate of change of the total number of lines embraced by the circuit. (See note at end of chapter.)

312. Direction of the Current.—We have already seen that the direction of the electromotive force is different according to the direction in which the lines of force cut across the wire. A simple consideration will serve to give the direction of the induced current. Let a magnet, or equivalent coil of wire carrying a current, be brought up to a closed circuit. The current induced by the motion represents a certain amount of energy, and more work was therefore required to move the magnet than if the circuit were not present. The same will be true on removing the magnet. The motion must therefore have been resisted by the force between the circuit and magnet. Of course a direct appeal to experiment will also show the direction of the induced current in each case.

313. Lentz's Law.—In 1834 the following law was announced by Lentz,* and is known as Lentz's law.

When an induced current is set up by the motion of a magnet or of a wire, the direction of the induced current is such as to impede the motion. Thus, to run a dynamo machine might require one hundred horse-power if the current were allowed to flow, while the same machine with the circuit open could be run by five horse-power.

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* Pogg., Ann. XXXI., p. 483.

The needles of sensitive galvanometers are often surrounded by a block of copper, in order that the currents set up in this block by the motion of the needle may bring it to rest.

Lentz's law shows that when a coil of wire is brought up to another coil carrying a current, the induced current is opposite in direction to the inducing; while on separating the two coils the opposite is true. This rule may readily be applied to determine the direction of an induced current due to starting or stopping the current in a neighboring coil.

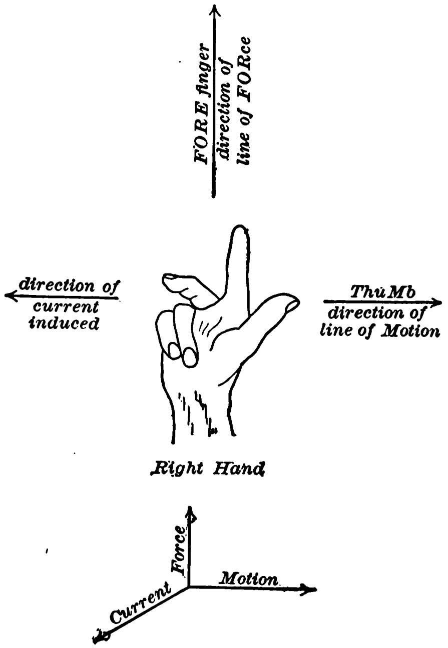

Fig. 126.

314. Fleming's Rule.—A rule more convenient for many purposes is easily remembered.

Open the thumb and two fingers of the right hand as shown in Fig. 126. The three will be found to stand mutually at right angles. Now if the FOREfinger be pointed along the lines of magnetic FORCE, and the thuMB in the direction in which the conductor MOVES, the second finger will point in the direction of the induced current.

315. The Rule Applied.—Applying this rule to special cases, we see, for example, that if the ring, Fig. 127, in a field which is not uniform is moved as shown by the arrow, then the large and small arrows around the ring indicate the electromotive forces in those places, and the current flows as shown by the larger arrow.

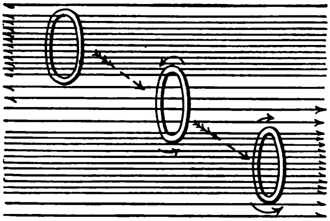
FIG. 127.

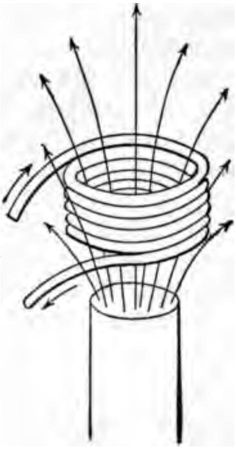
FIG. 128.

Or suppose a coil of wire to be slipped over the north pole of a magnet, Fig. 128. As the coil is lowered over the pole, the rule shows that the flow is in the direction shown by the arrows.

Since the current in this case is proportional to the number of lines of force cut, such a coil, connected with a ballistic galvanometer, is often used to find the strength of magnetic fields or the distribution of magnetism in a magnet.

316. Self-induction.—If the two wires connected with the poles of a battery are touched together and then separated, a faint spark is seen (with the very strong currents produced by the storage battery under these circumstances the spark is bright and gives a loud snap). Now if the same wires are connected with an electromagnet, so that the current flows through its coils, the spark is much more brilliant and loud. In either case there is evidence of the presence of a much higher electromotive force than that of the few cells of battery employed. The current seems to possess something of the nature of inertia, by virtue of which any attempt to stop it instantly (by opening the circuit) calls out a force sufficient to prevent such stopping, even to the extent of jumping across a layer of air.

317. Explanation of Self-induction.—This phenomenon is not very different in its nature from the induction already described in the case of two circuits. For suppose two coils of wire, *A* and *B*, Fig. 129. If a current is flowing in *A* and is suddenly stopped, a current in the second coil, *B*, will start up in the same direction as that in *A*. Now suppose that *A* and *B* are connected so as to form one coil, then the stopping of the current causes a collapse of the lines of force, and these lines, cutting the coil, set up a current in the direction of the current which is stopping. This induced current, added to the original current, causes it to be prolonged and continued after the electromotive force of the battery is removed. The more rapidly the current is caused to stop, the greater the electromotive force produced, so that no current can be made to stop instantly. If the current flows about a bar of iron, as in an electro-

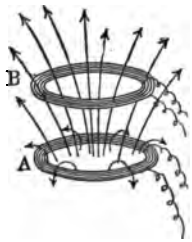

FIG. 129.

magnet, many more lines of force are set up, and their collapse causes a proportionately greater electromotive force. The analogy with inertia is very evident, the force which resists the stopping of a cannon-ball being greater the quicker one tries to stop it, so that no force can bring it to rest immediately.

On starting a current, a similar induction takes place, but its effects are less noticeable. The current on starting induces an opposite current, which produces the effect of weakening the original current. As this induced current dies out, the current rises to its full strength as calculated from the electromotive force and resistance by Ohm's law.

318. Self-induction in Wheatstone's Bridge.—There is no better way of showing the effect of self-induction than by Wheatstone's bridge, Fig. 130. Let the coil whose resistance is to be measured be placed at S, and its resistance found by sliding the contact C as usual till no deflection is obtained. In this measurement, the key K in the battery circuit must be kept closed. Now having found the balance, open the key K, and a momentary current flows through the galvanometer in the direction indicated by the arrows, as if the current in S were unwilling to stop when the battery circuit is opened. On closing K a current flows through the galvanometer in the opposite direction, as if the coil S had a greater resistance than was found when using a steady current.

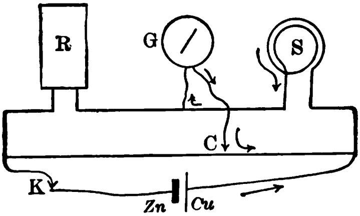

FIG. 130.

Both of these effects are much increased if a bar of iron is placed inside the coil *S*.

Partly on account of this action, the coils in resistance-boxes (p. 149) are made by doubling the wire before winding it on the spools, by which the effect is reduced as much as possible. It is also necessary, in measurements by Wheatstone's bridge, to close the battery circuit before the galvanometer circuit, to give this induced current time to die out before connecting the galvanometer.

319. Discharge of a Leyden Jar.—Interesting cases of mutual and self induction are connected with the discharge of Leyden jars. Prof. Henry pointed out that "the discharge is not correctly represented by the simple transfer of an imponderable fluid from one side of the jar to the other; the phenomenon requires us to admit the existence of a principal discharge in one direction, and then several reflex actions backward and forward, each more feeble than the preceding, until the equilibrium is obtained."* And Kelvin has showed by mathematical analysis † that the discharge must be oscillatory when the resistance of the discharging wire is not too great.

Here again we see that the current of discharge acts as if it had inertia, rushing too far, then flying back and forth like a bent spring or a pendulum, till frictional resistance finally brings it to rest.

320. The Spark Seen in a Revolving Mirror.—Conclusive proof of the successive discharges of a Leyden jar may be had by viewing the spark in a revolving mirror. If the steady flame of a gas-jet is viewed in a mirror which is rapidly rotating, the image is drawn out to form a band of light. If the flame is a vibrating one (such as may be produced by the vibration of an organ-pipe), the band of light

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* Scientific Writings of Joseph Henry, vol. I. p. 201.

† Phil. Mag., 4th ser., vol. V. p. 393.

will appear serrated (see Fig. 131). If the mirror be rotated very rapidly and the image of the spark observed in it, this image will be found to consist of a succession of bright flashes, showing that the spark is not one, but many.

321. Currents Induced by the Discharge.—Prof. Henry, who closely followed Faraday in his work on induced currents, early used these oscillating currents to form induced currents, and stated that the currents thus induced were capable of producing a more intense shock than the original discharge.[*]

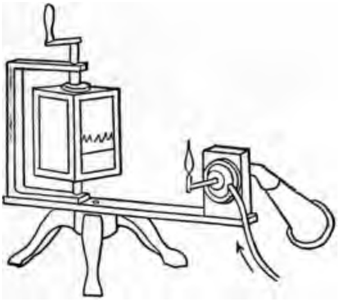

FIG. 131.—VIBRATING FLAME SEEN IN A ROTATING MIRROR.

Such oscillatory discharges have been used by J. J. Thomson to produce induced currents in tubes of rarefied gas (see p. 76) which had no electrodes passing through the glass and therefore could not have a direct current sent through them.[†] Similar discharges are employed in the experiments of Hertz, p. 237.

Other effects of self-induction are noticed under the subject of alternating currents.

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[*] Scientific Writings, vol. I. p. 105.

[†] Thomson's Recent Researches in Electricity and Magnetism, p. 92.

VALUE OF THE ELECTROMOTIVE FORCE OF INDUCTION.

It is easy to prove that the electromotive force of induced currents is equal (as well as proportional) to the number of lines of force cut per second. For the force exerted by a current of strength i, flowing in a wire of unit length on a unit pole placed at unit distance, is i, and on a pole of strength m, if the circuit is of length l, is iml. But the conductor is acted on by the same force. At unit distance from a pole of strength m the strength of the field, $\mathcal{H}$, is equal to m; therefore a conductor of length l in a field $\mathcal{H}$ carrying a current i is acted on by a force $\mathcal{H}il$. To move this conductor across the lines of force with a velocity v would require an amount of work $\mathcal{H}ilv$ per second. If the current i is due simply to the motion, and spent in heating the wire, the work so turned to heat, or ri^2 per second, must come from the work done in moving the wire, and $ri^2 = \mathcal{H}ilv$ and $ri = \mathcal{H}lv$.

Now $ri = E$, the electromotive force producing the current, and $\mathcal{H}lv$ is the number of lines of force cut in one second by the wire. Hence E is equal to the number of lines of force cut per second.

It evidently makes no difference whether the lines of force are due to a current in the conductor itself or in a neighboring conductor, or whether they come from a magnet.

Since the number of lines of force, N, enclosed by one coil, due to a current in a second coil, is proportional to the current in the second coil, N may be expressed as the product of two factors, thus: $N = Mi$.

Here M is seen to be the number of lines of force enclosed by one coil due to unit current in the second coil. It is known as the "coefficient of mutual induction." It may readily be proved to be the same whichever coil is considered as carrying the primary or inducing current.

In case of self-induction N may be similarly written as the product of two factors, $N = Li$; and L is seen to be the number of lines enclosed by any coil due to a unit current in the coil itself. It is called the "coefficient of self-induction."

In each case N means the total actual number of lines of force multiplied by the number of turns of wire by which they are enclosed, and the same is true of M and L.

CHAPTER XXIV.

LINES OF FORCE AND THE MEDIUM.

322. Currents Possess Kinetic Energy.—The phenomena of self and mutual induction furnish the strongest evidence that some medium is concerned in magnetic phenomena. Maxwell shows * that the apparent inertia of a current, due to self-induction, gives it a certain amount of kinetic energy. But the self-induction depends upon the medium, being greater if iron is present; hence the energy must be partly at least in the medium.

323. We Need Definite Conceptions.—The exact nature of the action in the medium and the mechanism by which it acts is at present unknown, yet to give definiteness to our conceptions it is well to endeavor to construct some artificial plan according to which we may suppose it to act. Such a scheme will give us a physical image which may suggest new relations and at least serve as a starting-point for some more complete and correct hypothesis.†

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* Electricity and Magnetism, part IV. chap. IV.

† In his lectures on Molecular Dynamics at Johns Hopkins University in the fall of 1884, Lord Kelvin showed various "models" of atoms, and remarked that he never thought he had a clear idea of anything unless he could make a model of it.

J. J. Thompson insists on the necessity of a student's adopting some physical conception of the processes going on in the electric field, adding: "It is no doubt true that these physical theories are liable to imply more than is justified by the analytical theory they are used to illustrate. This, however, is not important if we remember

324. Nature of Lines of Magnetic Force.—Quite independent of any theories as to the nature of lines of force or of ether, experiment requires us to notice—

First. That a current of electricity flowing in a rotary manner imitates a magnet.

Second. That wherever lines of force are present in matter there is a rotation of the ether (shown by the effect on polarized light) and of lines of electrical flow (shown by Hall's experiments).

Third. That there is energy present in a region occupied by lines of force. It is plain that electricity, magnetic force, and ether are closely connected; and the following scheme is suggested.*

325. Maxwell's Model.—Since lines of force repel each other and tend to shorten, let us assume that the medium about a magnet is made up of little globular cells which are set in rotation when any magnetic forces are operating. Centrifugal force then causes them to expand sideways and to shorten along their axes, causing the repulsion and shortening of the lines of force. Since all these cells rotate in the same direction, we must suppose further that they are separated by other particles rotating in the opposite direction. Maxwell suggested that we might consider these intervening particles to constitute electricity. They move with more or less friction through conductors, but in nonconductors, as air or glass, they are held by an elastic fastening to one spot from which they may be slightly displaced, but to which they will immediately return when the force

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that the object of such theories is suggestion and not demonstration. Either experiment or rigorous analysis must always be the final court of appeal; it is the province of these theories to supply cases to be tried in such a court." (Recent Researches in Electricity and Magnetism, page vii of Preface.)

* Due originally to Maxwell. For an excellent account of the hypothesis see Fleming's "Alternate Current Transformer," vol. I. p. 325 *et seq.*

is removed (as electricity can flow in conductors, but in non-conductors only suffers elastic displacement).

326. Connections of Cells and Particles.—These cells and particles turn freely about their own axes, but never slip on each other. Now suppose that such a cell, *A*, Fig. 132, were set in rotation; the particle *C* will be carried along to a new position, *C′*, rolling along *B*, because the inertia of *B* will prevent it from immediately rotating as rapidly as *A*. As the inertia of *B* is gradually overcome, *C* is no longer displaced, but simply rotates between *A* and *B*.

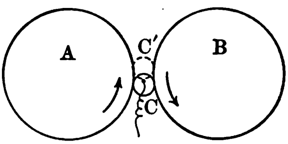

FIG. 132.—DIAGRAM OF ARRANGEMENT OF CELLS AND PARTICLES. (FLEMING.)

327. Explanation of Induced Currents.—Consider a group of such cells and particles constructed to transmit rotation from one place to another, and apply it to the phenomena of induced currents.

A conducting wire *AB*, Fig. 132, is filled with electrical particles which are free to flow along it (with more or less friction). Touching the conductor and its particles are the cells F_1, which are connected by a layer of electrical particles e_1 with another set of cells, F_2, and so on to F_7, which rest against the particles in the second wire, *CD*. Now let a flow of particles in *AB* take place from *A* toward *B*. All the cells F_1 touching these particles are set in rotation. The cells press against the particles e_1, and would set them into rotation but that they rest against the cells F_2, and on account of the inertia of these cells the particles are at first displaced toward the left, constantly exerting a force upon F_2 to set them in rotation. As the cells F_2 are set in motion the same process is repeated further on in the medium, and the rotation is thus transmitted to the last row, F_7, which rests against the particles in the wire *CD*. Since these particles are free to move, they start off toward the left, their motion forming the induced current. But while not held firmly in place, yet they are hindered in their motion by friction, which acts as a constant drag. This friction against the cells beyond sets these latter into rotation, and soon the

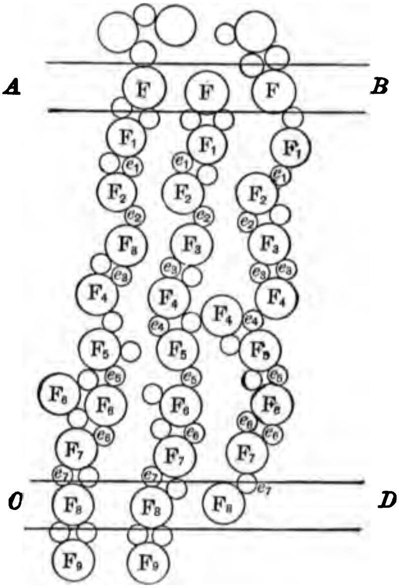

Fig. 133.

current ceases, cells and particles alike rotating in the conductor exactly as in the air about it. The induced current has now died out and everything seems to be in just the same condition as if no conductor were present at *CD*.

But if the current in *AB* is stopped, the presence of *CD* is again felt. The cells F_1 are checked; the inertia of those beyond crowds the particles e_1 toward the right as far as the elastic connections allow. These cells e_1 thus press upon F_2 and forces are transmitted through the medium exactly as on starting the current, till the wire *CD* is reached, where the particles are driven toward the right and an induced current set up which lasts as before until frictional forces bring it to rest. Thus the energy given to the cells in starting the current is all recovered by the induced current in *CD* and by the continuance of a current in *AB* after the removal of the electromotive force.

Thus, according to this model, electric displacement currents take place in the non-conducting medium similar to the induced currents in the wires. Indeed these latter are produced as a result of the displacement currents dying out.

328. Starting of a Current in a Wire.—A very similar action takes place in any wire in which a current is started. A battery *C*, Fig. 134, has its poles *AB* charged plus and minus respectively, i.e., particles have flowed around from *B* to *A*. Since the space was already filled with particles previous to this charging, there was at the same time a displacement of particles in the air from *A* toward *B* as far as their elastic connections would allow them to go. (A displacement similar to this was suggested in the chapters on Electrostatics. See Chapters III and V.) Now let the wire *DEF* be connected at the ends *D*, *F*, to the poles *A* and *B*. They will be charged by this contact, i.e., there will be a flow of particles into the ends of the wire, and at the same time a displacement toward the right of the particles in the medium between *D* and *F*. Exactly as before explained, these particles by their motion will set the cells and particles beyond in motion and the motion thus produced will be transmitted from row to row until it

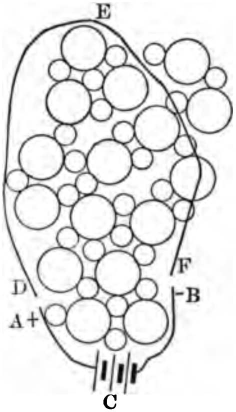

FIG. 134.

reaches the farther parts of the wire, where a flow of particles will be set up.

The particles (electricity) are thus seen to flow along the wire from one pole to the other. But the force which sets them in motion acts through the medium. The current is not only begun, but is kept up afterwards also by the motion of the particles, produced in the battery as the result of chemical actions and transmitted through the air to every part of the wire.

329. The Energy Travels through the Air.—We are thus naturally led to the idea that the energy of a current travels through the air. It is as though space were filled with cog-wheels, geared together and kept in motion by the battery. As these gears work without friction, they themselves use up no energy, but in the wire the flow is accompanied by friction and energy is used up, i.e., converted into heat.

As stated in the note, p. 231, it will not do to base theories upon such reasoning as this. The suggestions here made must be tested by experiments and mathematical discussion. In a paper on the Transfer of Energy in the Electromagnetic Field,* Poynting shows that the transfer of energy through the air meeting the wire perpendicularly, as above described, leads to correct results mathematically considered. This does not prove that the energy travels in this way; only that it may so travel. The importance of the medium in electrical phenomena is more and more evident, and the tendency is toward a belief that the energy does travel in some way through the air and not along the wire.

330. Time of Induction.—If the electromagnetic induction is propagated through the medium in any such way as here described, it might naturally be expected that a certain

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* Phil. Trans. 1884, part II. p. 343.

time would elapse before the induction would be felt in a second conductor. If no time were required, the matter would be in doubt; but if time does elapse, the induction must be by means of some medium. It cannot be by a direct action at a distance.

On page 169 was described a method for finding the ratio of the number of units in any electrical quantity as measured by electrostatic and electromagnetic methods, and it was there stated that Maxwell had proved that any electrical disturbance would travel through the air at a velocity equal to v (the ratio of the number of units) thus found.

331. Hertz's Experiments.—At the time of Maxwell's work there was no direct evidence that such disturbances actually required any time; and indeed since v is equal to the velocity of light, it would plainly be very difficult to detect any difference between the time when a current was started in one wire and the time when the inductive action was felt in a neighboring wire. The measurement of this difference in time was successfully accomplished by Prof. Hertz in connection with his study of the nature of electrical oscillations.

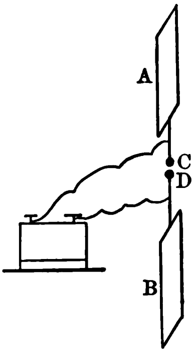

FIG. 135.

332. Hertz's Apparatus—The Vibrator.—In his experiments* Hertz employed two square brass plates, A, B, Fig. 135, each carrying a copper wire with a knob, CD, on the end. These were arranged as shown in the figure, and one

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* The original papers are collected and published (in an English translation) under the title "Electric Waves, Hertz." An excellent résumé is contained in Fleming's "Alternate Current Transformer," vol. I. p. 411, and a mathematical discussion of the whole subject in "Recent Researches in Electricity and Magnetism," J. J. Thomson, p. 388.

was connected to each of the secondary terminals of an induction coil. On working the induction-coil the plates are charged and sparks pass between the knobs *CD*. (For the explanation of the working of this coil see p. 268.) As explained in connection with the Leyden jar (p. 228) the discharge is not a simple flow from one knob to the other, but a succession of sparks as the charge rushes across in one direction, then back in the opposite direction; vibrating rapidly back and forth until it soon dies out. On the farther wall of the hall in which the experiment was tried was hung a sheet of zinc 13 feet high and 7½ feet wide, connected at its upper and lower edges to gas and water pipes. The vibrating current can thus induce vibrating currents in this metal sheet.

333. Waves of Induction.—Now if a conducting wire of proper form (the "resonator") is held between the "vibrator" and the zinc sheet, the wire will feel the force of induction from both; and if this force travels instantaneously, it will make no difference how far from either the wire is held, except as distance may make the influence of the one or the other weaker. Very different will it be if any time is required for the force to travel. For now the wire may be held at such a distance from the zinc sheet that the induction exerted by this shall be felt at the same instant as that exerted by the vibrator; while at some other point the forces will arrive at just such times as to neutralize each other's influence. The zinc sheet thus seems to reflect the waves of electric induction sent out by the vibrator and the room is filled with nodes and loops of elec-

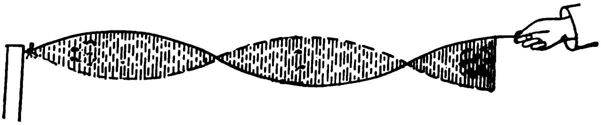

FIG. 136.

tric force just like the nodes and loops on a rope, one end of which is fastened, while the other is shaken regularly by the hand (Fig. 136). Such waves are called stationary waves, and may be produced whenever direct and reflected waves meet and interfere.

Fig. 137 shows the arrangement of apparatus adopted by Hertz to test this question. The primary conductor or vibrator, Fig. 135, is set up at one end of the hall, while a sheet of zinc, *Z*, Fig. 137, is hung at the opposite end.

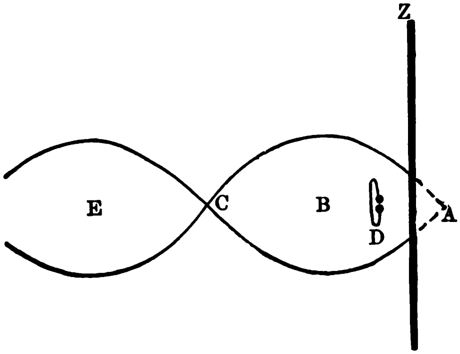

FIG. 137.

334. The Resonator.—A circular conductor *D* is used to test the presence of inductive force, and consists of a wire bent into a circle of 14 inches radius. The ends of the wire are brought nearly but not quite together so that a small spark will be seen between the ends of the wire if there is an electromotive force sufficient to produce a spark. Now let this circle be held with its plane parallel to the conducting sheet and with the spark-gap turned to one side, half-way between the highest and lowest points. When so placed and held near to the vibrator, it is found that a current surges up and down in the wires of the circular conductor and sparks appear strongly at the spark-gap. When the dimensions are as here given, the current in the circle has the same natural period of vibration as that in the vibrator, and this is necessary for the production of vigorous sparks.*

335. Results of Hertz's Experiments.—With the apparatus arranged as in Fig. 137, let us place the circular conductor near the zinc screen. "This is what we observe: Just at the conducting metallic surface there are no sparks, but they make their appearance at a very small distance from it; they increase rapidly, are comparatively strong at *B*, and then again diminish. At *C* they are exceedingly feeble, but become stronger as we proceed further. They do not, however, again diminish, but continue to increase in strength, because we are now approaching the primary oscillation. If we were to illustrate the strength of the sparks along the interval *AE* by a curve, . . . we should obtain almost exactly the curve which has been sketched" † (Fig. 137).

336. Induction Requires Time to Travel—Its Velocity.—There is therefore no possible doubt of the presence of a wave of inductive force, and therefore can be none that this force is exerted by means of some medium. But Hertz's experiments go farther than this: they enable us to measure approximately the velocity of this wave. For the velocity of any wave is evidently equal to the product of the wave-length and the number of waves in a unit of time. The length of one wave as measured by Hertz was 4.8 meters; the number of vibrations per second, calculated as well as might be from the dimensions of the conductor, was 50 000 000; hence the velocity of this wave of induction is 240 000 000 kilometers per second. The velocity of light is 300 000 000 kilometers per second; as the measurement of

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* Just as one tuning-fork will set another near it in vibration if the second is exactly tuned to the first, but not otherwise.

† Hertz's Electric Waves; Jones's translation, p. 130.

the wave of induction is only a rough one, we can only say that this wave travels with about the velocity of light.

337. Other Experiments.—These experiments have been carefully repeated by many physicists, and no doubt remains that the facts are exactly as stated by Hertz, and that they are to be explained only by assuming the action to take place by means of a medium quite similar to or identical with the luminiferous ether.

The waves discovered by Hertz and just described are very different from light-waves in one respect. The waves of light are about fifteen million times as rapid as these, while each wave is $\frac{1}{15000000}$ as long. There are therefore differences in their properties, but none sufficient to cast serious doubt on their immediate relationship.

338. Light-waves and Waves of Induction—Refraction.—Waves of light travel at a slower velocity in solid and liquid bodies than in air; and this difference of velocity causes them to be bent out of their path, or refracted to one side, if they pass through a wedge or prism of such a substance. Prof. Hertz made a large prism of pitch, and by placing this in the path of his "electrical waves" found that they were refracted in exactly the same way and by the same amount.

339. Reflection.—That the Hertz waves are reflected by sheets of metal is sufficiently evident from the experiments above described. Hertz, in some of his work, used concave parabolic mirrors, to increase the strength of his "rays," and these were found to act as reflectors just as with light-waves.

340. Opacity of Conductors.—In this power of conductors to reflect the waves we have the explanation of the fact, correctly interpreted by Maxwell, that the metals and carbon are opaque, while nearly all other substances are transparent. As already explained, the opacity of wood, stone, etc., is largely due to their structure; when examined in thin sections these substances will be found far more transparent than any metal of the same thickness. The other principal exception is the large group of transparent liquids which conduct electrolytically. These substances are opaque to the Hertz vibrations, and indeed many of them are opaque to vibrations only a little longer than those which affect our eyes.

The properties of the medium in transmitting these vibrations are evidently such as to justify, and to require, views, as to electric charges and electric displacements, something like those which were presented in the chapters on Electrostatics.

CHAPTER XXV.

COMMERCIAL PRODUCTION OF INDUCED CURRENTS.

341. Induction is of Commercial Importance.—If the study of induced currents has revolutionized our ideas of the nature of electricity, the application of these discoveries to industrial purposes has been hardly less revolutionary. Nearly all the modern uses of the electric current, electric lighting, railways, motors, etc., depend for their existence upon the invention of the dynamo which produces currents by induction.

342. The Dynamo.—The dynamo * consists essentially of three parts: a powerful electromagnet for producing lines of force; a series of wires for cutting these lines; a collecting device to carry the induced current to the circuit over which it is to be sent.

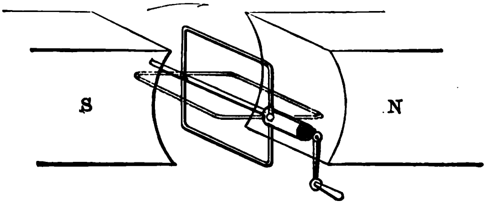

FIG. 138.

343. The Armature.—In Fig. 138, *N* represents the

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* The name "generator," often applied to this machine, may easily mislead. It may perhaps be said to "generate" a current, but it no more generates electricity than a pump generates water.

north and *S* the south pole of the electromagnet, the lines of force running in nearly straight lines from *N* to *S*. A rectangle of wire, called the armature, is so fixed that it can rotate between these poles. If this rectangle turns through 180°, each of the horizontal sides cuts all the lines of force; during the next half-turn all the lines are again cut, but in the opposite direction. In this rectangle there is thus an alternating electromotive force whose period is the same as the period of rotation of the wire. If it is desired to obtain from this machine a current that shall flow always in the same direction (a "direct" current), the connections must be reversed at every half-turn.

344. The Commutator.—This is readily done by connecting the ends of the wire to the halves of a ring as shown in Fig. 139. Two half-rings of copper, r_1 and r_2, are placed upon an insulating core, *C*; one end of the wire rectangle is connected with r_1 and the other end with r_2. Two collecting brushes, b_1 and b_2, are placed 180° apart, so that each rests on one of the half-rings. Thus during one half of the revolution the collecting brush b_1 is connected with one end of the wire, during the other half-revolution to the other end; and the electromotive force in the external circuit is always in the same direction.

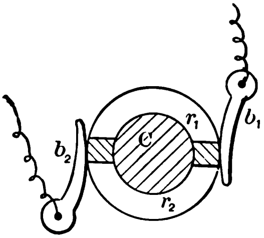

FIG. 139.

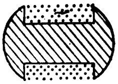

FIG. 140.—SIEMENS' SHUTTLE ARMATURE.

345. Siemens' Shuttle Armature.—Since each wire that cuts a line of force produces its own electromotive force, it is best to use several or many turns of wire; and since the lines of force will be more numerous if a mass of iron is placed between the poles of the magnet, the coils are wound upon an iron core. This leads to the form of armature shown in section in Fig. 140.

346. The Current is Fluctuating.—By examining Fig. 138 we see that while the plane of the coil is vertical the wires are moving nearly parallel to the lines of force, and consequently the electromotive force is slight. When at 90° from this position the wires are cutting the lines of force most rapidly, and the electromotive force is proportionally greater.

The current produced by such an armature will not be of uniform strength, but may be represented by a curve as in Fig. 141, which represents the current nearly as it exists in the armature. Since the current passes through the commutator and always flows in the same direction in the external circuit, we must represent it here by the curve, Fig. 142. In these curves the horizontal distances measured along OX represent the angles through which the armature has turned from its vertical position (Fig. 138), while the height of the curved line above OX represents the strength of the current corresponding to that position.

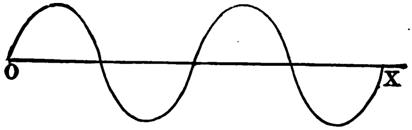

FIG. 141.

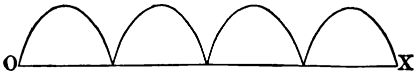

FIG. 142.

The passing of the curved line in Fig. 141 below the line OX indicates that the current has changed its direction, while in Fig. 142 the curve is always above the line OX but at different heights, corresponding to the varying strength of the current.

347. Modified Siemens Armature.—For most purposes it is desirable to have the current more uniform in strength; hence it is customary to wind a number of coils around a cylinder, so arranging them that while one coil is cutting the lines of force most rapidly, the others shall be in intermediate positions. Let us consider an armature in which there are two such coils placed at right angles. These are so connected to the commutator that the electromotive force is the sum of the electromotive forces of the two coils, one of these being zero when the other is a maximum. Fig. 143 shows the separate electromotive forces due to the two coils, and Fig. 144 shows the way these electromotive forces combine to give one which is much more steady in value than either one separately.

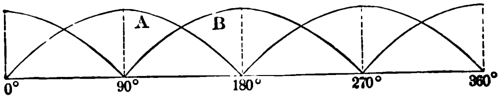

FIG. 143.

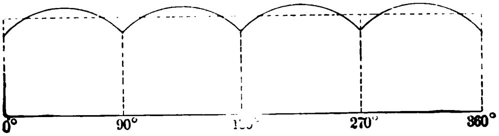

FIG. 144.

Fig. 145 represents the ordinary practice, employing a large number of coils distributed all over the cylinder. The electromotive force of such an armature hardly fluctuates at all, and hence the resulting current is practically uniform.

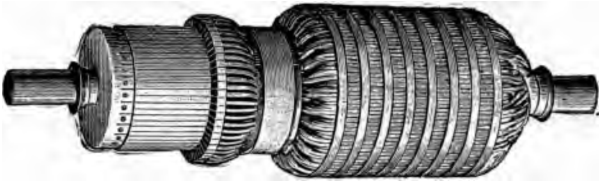

FIG. 145.

348. The Gramme Armature.—Another armature in very common use is the Gramme ring. The action of this may be understood by reference to Fig. 146. The ring, which is of iron, is placed between the poles of the magnet, and because of the greater reluctance of the air most of the lines of force are in the iron. If a coil of wire is wound on the ring and the whole is rotated, the wires on the outer circumference of the ring will cut the lines of force entering the ring, and if the direction of motion is as indicated in the figure, the current in the outer part of the coil is toward the observer.

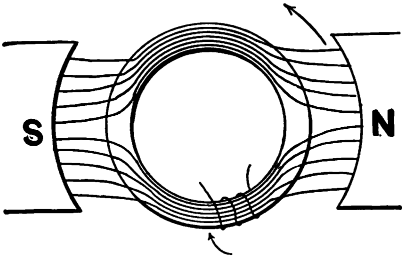

FIG. 146.

The Gramme ring consists of a series of such coils wound on an iron core (Fig. 147) and connected to a series of copper bars, exactly as is the case with the Siemens armature.

Copper or carbon brushes resting on these bars convey the current to the external circuit.

349. The Core is Laminated. — Whichever form of armature is used the iron core upon which the coils are wound must be of thin sheets of iron insulated from each other by thin paper or a film of oxide. If this is not done, currents will be set up in the core exactly similar to those in the wires, and the energy required to maintain these currents will be wasted, while the currents will make the armature dangerously hot.

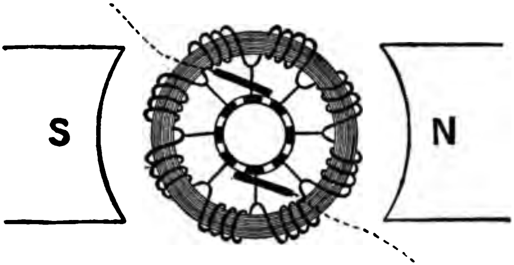

FIG. 147.

350. The Field is Self-exciting.—The magnets which produce the lines of force were, in the first machines, permanent steel magnets. Later they were electromagnets, and the current supplying them was furnished by a small machine which had permanent steel field-magnets. Modern machines supply their own current; for it is found that the iron from which the magnets are made always retains enough magnetism to induce a small current in the armature when the latter is rotated. This current is conducted around the field-magnets and makes them stronger; this stronger magnet gives rise to a stronger current in the armature, and the machine thus "builds up" and soon attains to its maximum power.

351. Series and Shunt Dynamos.—There are two principal methods of employing the current to excite the field-magnets. In one (the "series" machine) the whole current is led a few times about the magnets (Fig. 149). In this machine any cause which weakens the current also weakens the field-magnets and lessens the electromotive force. Hence this form of winding is of limited usefulness unless accompanied with some automatic regulator.

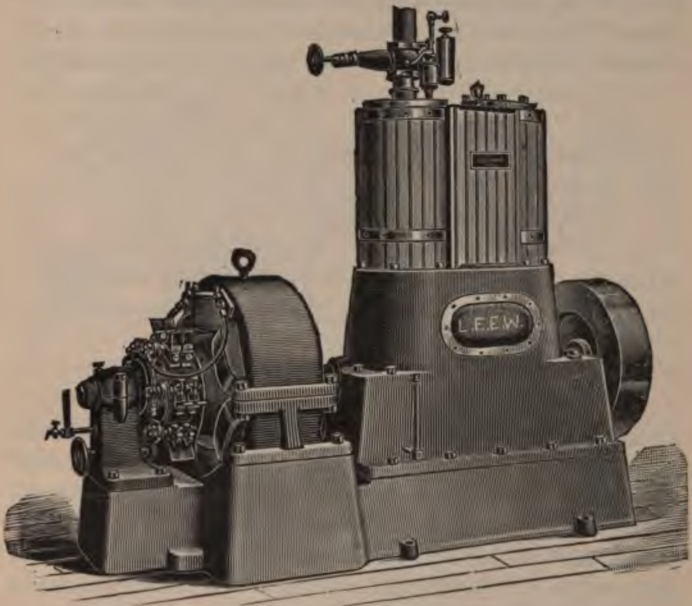

FIG. 148.—MULTIPOLAR DYNAMO, DIRECT CONNECTED TO STEAM-ENGINE.

In the "shunt" machine (Fig. 150) a small part of the current is led many times about the field-magnets; this part of the current being employed for this purpose only, while the rest of the current is employed usefully in the external circuit. In this machine the electromotive force is nearly independent of the current in the external circuit.

352. Compound-wound Dynamos.—For some purposes machines are employed in which the field is excited mainly as in the shunt machine, but in addition the whole current is carried a few times about the magnets (Fig. 151). The effect of this is that as more current is required in the external circuit, the series coils assist the electromotive force, which is thus kept more constant than even in the shunt machine. These machines are well adapted to incandescent lighting where the regulation of the lamps requires a constant electromotive force.

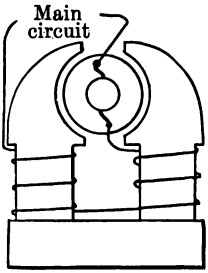

FIG. 149.

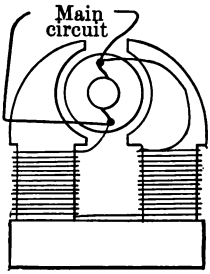

FIG. 150.

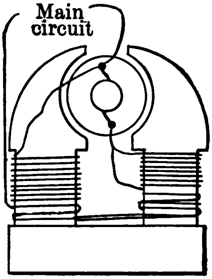

FIG. 151.

353. Motors.—The electric current has been found of great value for the distribution of power. The dynamo is driven by a steam-engine or water-wheel, and the energy of the electric current is transmitted by means of a wire to any place where power is desired, when a motor is connected to the wire and power is obtained.

The electric motor depends for its action on the principle explained on p. 129, that a magnet exerts a force on a conductor carrying a current. Whenever a current flows in a wire which runs at right angles to lines of magnetic force, the conductor is impelled at right angles to its length across the field. This is excellently illustrated by the D'Arsonval galvanometer, where this force is used to measure the strength of the current in the wire. An examination of

Fig. 138 will show that the dynamo is very much like a D'Arsonval galvanometer, except that the coils are so arranged that as one moves away from the position where it cuts the lines of force, the commutator changes the connections from that coil to another. Hence the dynamo makes an excellent motor, and, if furnished with a current, will rotate and will cause whatever may be attached to the armature to rotate with it.

The field-magnets of the motor may be series or shunt wound (Figs. 149 and 150); the series winding being adapted to motors of variable speed, like street-cars, and the shunt to machines where a uniform speed is needed.

354. Back Electromotive Force of the Motor.—Since the motion of conductors across lines of force produces an electromotive force, there is evidently such an electromotive force in the armature of a motor. This electromotive force opposes the flow of the current and is, indeed, the principal obstacle to the flow of the current. That part of the electromotive force of the current which is spent in overcoming the resistance of the wire in the motor is wasted in heating this wire, and only that part which is used in overcoming the back electromotive force of the motor is usefully employed in driving the motor. Therefore the same conditions which are useful in aiding the power of a dynamo are of similar value in increasing the usefulness of the motor: a good dynamo makes a good motor.

355. The Force on the Wire of a Motor.—The force with which a wire carrying a current tends to move across a magnetic field is the same as the force which must be exerted to carry it across such a field. The value of this force was calculated on p. 230 and found to be $\mathcal{H}li$, i.e., proportional to the intensity of the field, the strength of the current, and the length of the wire.

356. Alternators.—The dynamos already described are provided with commutators which change the connections between the armature and the external circuit so that the latter carries a continuous current. If one end of the wire rectangle in Fig. 138 were always connected to one end of the circuit, and the other to the other end of the circuit, an alternating current would be produced; which might be represented by Fig. 141, in which the vertical distances would then represent current strength. Such machines are called "alternators." They are commonly accompanied with a small direct-current machine called the "exciter," which furnishes the current for their field-magnets. One end of the wire on the armature is connected with one ring, and the other end with a second ring; brushes resting on these rings carry the current to the external circuit.

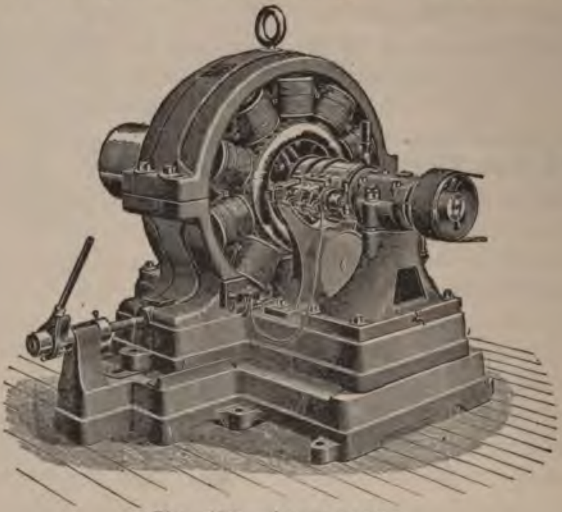

FIG. 152.—ALTERNATOR.

357. Loss of Energy on the Line Wire.—The special advantage of the alternating current is to avoid the loss of energy in the line wire. Whenever a current is carried over a wire, the loss of energy by heating the wire is proportional to Ri^2 per second, if R is the resistance of the line and i is the current flowing in it. (See p. 173, eq. 2.) The whole energy given to the line in a second is Ei (p. 172). Now if a large amount of energy is to be transmitted by a wire, either E or i must be large. If i is increased, the line is heated, and energy wasted, in proportion to the square of i; therefore R must be made very small or too much energy will be lost in this way. An increase of E does not increase the heating of the line. Therefore for the arc lights used in streets it is customary to employ pressures of 2000 to 6000 volts. Where the current is to be used for lighting residences or for running motors in factories, etc., such pressures would be highly dangerous in case of accidental contact with the wires. Here the pressure should hardly exceed 200 volts. The alternator now shows its value, since it enables currents to be transmitted over the line at high pressures and then reduced to low-pressure currents where they are to be used. To accomplish this, transformers, or converters, are employed.

358. Transformers.—The transformer consists of an iron core wound with two coils of wire; the one (Fig. 153, *B*) contains many turns of fine wire, the other a smaller number of turns of coarser wire. The high-pressure current from the alternator passes through the fine wire and magnetizes the core. The lines of force thus produced cut across the windings of the coarse coil and set up an electromotive force in them; and these are connected to the house wires and furnish the current for lighting purposes.

The pressure is very nearly proportional to the number of windings, and it is thus possible to adjust it to produce any desired voltage. Ordinary practice in this country is to use a pressure of 1000 volts in the street line and 50 in the secondary or house circuit.

It is evident that the transformers add to the cost of the plant; hence where business is compact it may be more

FIG. 153.

A, THE TRANSFORMER.
B, CROSS SECTION SHOWING THE FORM OF THE IRON CORE.

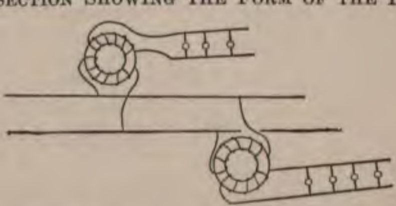

FIG. 154.—DIAGRAM SHOWING HOW TRANSFORMERS AND LAMPS ARE CONNECTED TO ALTERNATE CURRENT MAINS.

profitable to distribute the low-pressure current from the central station through heavy conductors; but where the lighting is scattered the cost of the conductors would make this impossible and the alternating system as above described is the only one available.

359. Hysteresis.—Attention has already been called to the necessity of constructing the armatures of dynamos of thin sheets of iron to avoid currents in them. The same necessity exists in the case of transformers. Another cause of loss of energy beside the currents in the iron is to be found in a peculiarity of the iron itself.

On p. 201 it was explained that the retentive force of iron causes part of its magnetism to remain when the magnetizing force is withdrawn; the magnetization always lagging behind the force. Because of this lag it requires work to magnetize iron and again to demagnetize it, and the area of the curve is just equal to the energy used up in a complete reversal of magnetism. This energy is much greater for hard steel than for soft iron (see Fig. 155, I and II). This

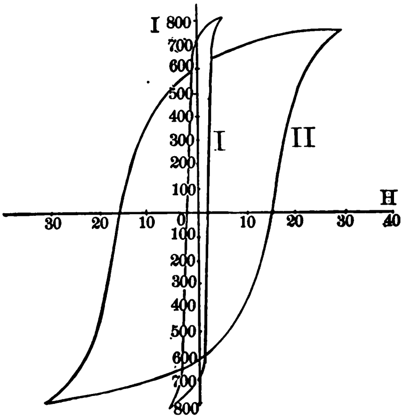

FIG. 155, I.—SOFT IRON. II. STEEL.

property of iron is known as hysteresis (a "lagging behind"), and to avoid it the cores of armatures and transformers are made of carefully selected soft iron or mild steel and well annealed. A certain loss from this cause is unavoidable, but much of the excellence of a transformer depends upon the proper selection of the iron.

CHAPTER XXVI.

SOME PROPERTIES OF ALTERNATING CURRENTS.

360. The Sine Curve.—While alternating currents are very useful for transmitting energy, yet their employment has introduced many complications and difficulties.

In order to study their properties it is customary to assume that the current can be represented by a sine curve (Fig. 156), as was indicated on page 252. This curve is constructed by laying off on a horizontal line distances equal to the arcs of a circle, 1, 2, 3, 4, etc. At the points 1, 2, 3, etc., thus located on this line erect perpendicular lines equal to the heights of the corresponding arcs, 1, 2, 3, etc., above the horizontal diameter of the circle. The points thus found are connected by the continuous lines as shown. This is called a sine curve because the vertical distances are the sines of the horizontal. It is the simplest of all periodic curves and often represents the curve of the alternating current with considerable accuracy. In other cases the results of calculations made by means of this curve require decided modification to apply them to actual cases.

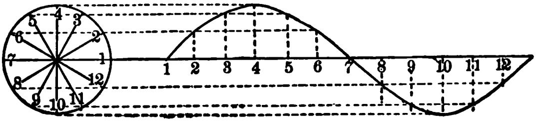

FIG. 156.

361. "Virtual" Volts and Amperes.—The first question to ask is what we mean by one ampere in the case of an alternating current. Since the actual current has all values from zero to its maximum value, the word is ambiguous; and the difficulty is increased by the fact that the "average" value of the current is zero, since it has as much flow in the negative as in the positive direction. The current, however, is to be used for producing heat or some other form of energy, so that "one ampere" is understood to mean a current that will produce as much heat in a given resistance as would one ampere of continuous current. "One volt" in alternating currents is understood to mean the electromotive force that will produce this current in a circuit which has no self-induction and which has a resistance of one ohm. Amperes and volts measured on this basis are known as virtual amperes and volts. Thus understood, a current of one ampere which follows a sine curve fluctuates between all values from + 1.41 to −1.41 amperes; and the same is true of one volt which means a pressure varying from + 1.41 to − 1.41 actual volts.

362. A Sine Electromotive Force—Self-induction Zero.—If an alternating electromotive force such as is represented by the sinuous line, Fig. 155, is applied to the terminals of an incandescent lamp, or any resistance which has no self-induction, the resulting current will be proportional to the electromotive force, and at each instant may be calculated from the electromotive force at the same instant by Ohm's law

$$i = \frac{E}{R}.$$

363. Resistance Zero.—But when the circuit includes wire coiled up so as to possess an appreciable self-induction, this is no longer true. Every change in the strength of the current will now cause an electromotive force in the circuit which will resist such a change. Hence the electromotive force applied to the circuit must overcome both its resistance and this back electromotive force due to self-induction.

Let us imagine a coil with practically no resistance and large self-induction, and let the line *A*, Fig. 157, represent the current in this coil. During the time while the current is increasing in value as shown by the first part of the curve, the back electromotive force, due to self-induction, will be strongest, and therefore this is the time when the applied electromotive force must be greatest; as the current near the top of the curve increases less rapidly in value, the electromotive force required is less; while at the top the current is not changing for the instant, and for this instant the electromotive force required to overcome the self-induction is zero. Hence the curve *B* indicates the electromotive force which will produce a current represented by *A*, in a circuit whose resistance is zero. We notice —

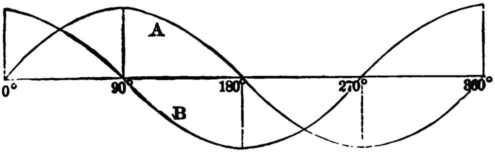

FIG. 157.

1st. That the value of the current is less than if the self-induction were absent;

2d. That it reaches a maximum at a later time than the electromotive force—in fact, at a time corresponding to a distance of 90° on the sine curve of Fig. 156.

364. Self-induction and Resistance both Present.—If both self-induction and resistance are present, their effect will be combined. For any current there will correspond an electromotive force sufficient to overcome the resistance, which will come to a maximum when the current is a maximum, and a further electromotive force to overcome the self-induction which will come to a maximum when the current is zero. The whole electromotive force will be the sum of these, but its maximum value cannot be found by adding the maximum values of the separate electromotive forces; for they come at different times. The theory of these quantities shows that as they are 90° apart, they may be added like two lines which are 90° apart.

Thus if E is the total electromotive force, Ri is that required to overcome the resistance and pLi required to overcome the self-induction, then

$$E^2 = \overline{Ri}^2 + \overline{pLi}^2.$$

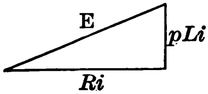

FIG. 158.

This can be represented by the sides of a right-angled triangle, Fig. 158.

365. Impedance.—Since $E = i\sqrt{R^2 + p^2L^2}$, Ohm's law in its simple form $\left(i = \frac{E}{R}\right)$ is no longer true. In place of this we have the equation $i = \frac{E}{\sqrt{R^2 + p^2L^2}}$, and the denominator is known as the impedance of the circuit.

The quantity p which appears in these equations depends upon the rate of alternation, being equal in fact to 4π times the number of reversals of current per second.

366. Difficulties of Measurement.—Still further difficulties arise in alternate-current work when we undertake to make measurements. Galvanometers become useless, and for measuring either the current or electromotive force we are nearly restricted to the electrodynamometer (p. 142) or to instruments like the Cardew voltmeter (p. 177) which depend upon the heating produced by a current. The quadrant electrometer and multicellular voltmeter can also be used to measure electromotive forces. These instruments are none of them as delicate as the galvanometer.

Moreover, when we come to measure the power given out by an alternator, in watts, we are met by the serious difficulty that the average volts multiplied by the average amperes no longer gives watts. It makes all the difference in the world whether the volts come to a maximum at the same time as the amperes, or 90° later. In the first case, this product will give the watts directly. In the latter, the number of watts must be found by multiplying the current strength at each instant by the electromotive force at the same instant, and adding all these products. Calculation shows that in case the current is 90° behind the electromotive force, the sum of the products is zero, because there are as many positive as negative values of the product.

367. Choking Coils.—It follows that while the introduction of self-induction into a circuit makes the current weaker, it does so without using up power, as would be the case if a resistance coil were introduced. Advantage is taken of this fact, and such currents are weakened, if necessary, by introducing coils of large self-induction (called choking coils) into the circuit.

368. The Wattmeter.—The instrument most depended on for power measurement in such cases is the wattmeter. This is an electrodynamometer through whose fixed coils the whole current passes. The suspended coil is connected in shunt with the circuit, where the power is to be measured (Fig. 159), and has a high resistance in series with it. If the current in the suspended coil may be considered as proportional to the electromotive force applied to it, and as having its maximum at the same instant (in other words, if the resistance of the suspended coil is large as compared with its self-induction), the readings of this instrument will give the average value of the products of the current and electromotive force: it is then a true measurer of the watts given to the circuit.

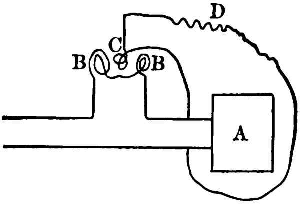

FIG. 159.—DIAGRAM OF WATTMETER CONNECTIONS.

369. Skin Conduction.—One further peculiarity of alternating currents deserves mention. Since the lines of force in their motion travel through the air, they strike the outside of a wire first. They are somewhat retarded in their motion by the current which they set up, and only later succeed in cutting across the interior parts of the wire. Hence in case of rapid alternations it is quite possible for the current to be reversed before the current in the inner parts of the wire has been fully established. The current will not be uniformly distributed through the whole conductor, as with continuous currents, but will be stronger in the outer layers. Inside a large conductor it may be zero, or even in the opposite direction to that in the outside. Where large conductors are to be employed for carrying rapidly alternating currents, they should be made of thin strips, so as to have a large surface.

370. Lightning.—While the sources of atmospheric electricity are quite unknown, yet the progress of knowledge as to the action of lightning requires us to treat it in connection with alternating currents. Long wires carried for miles through the air and then leading to delicate apparatus present an opportunity for damage that lightning has not failed to make the most of, and the need for protection has compelled attention.

In a thunder-storm, the charged cloud and the charged earth form the two coats of a great condenser, and the flash of lightning is like the discharge of a Leyden jar. Often there are several flashes back and forth following each other with great rapidity, in place of a single flash; and even when the flash is single the rapid increase and decrease of the strength of the current calls all the phenomena of induction into prominence.* The following points are noticeable.

If the discharge takes place along a conductor, the current will be principally confined to the surface of the conductor.

It will jump across an air-space rather than go round by a path of greater self-induction. The resistance of the path is usually of little importance compared with its impedance.

Discharges may induce currents in any conductors. The flow along a lightning-rod may be accompanied by others along gas or water pipes or any other masses of metal.

On account of the oscillating nature of the discharge, oscillations may be set up in conductors whether insulated or grounded, as in Hertz's experiments. Flashes may therefore take place between different parts of the same metallic conductor wherever they come near together, or between two conductors which are thoroughly connected to the ground.

371. Practical Suggestions.—Franklin's lightning-rods, well applied, afford a considerable degree of protection, but the following statements may prove of value.

Lightning-rods should go to the highest parts of a house, but should not extend much above them. A good many sharp points are desirable. They should then go down to the ground by the shortest path, avoiding sharp bends. A

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* An excellent and full discussion of the whole subject is contained in "Lightning Conductors and Lightning Guards": Lodge.

rod down each corner is desirable. The lower end of the rod must be well grounded. Connect it firmly and solder it to water or gas pipes where these enter the ground: or otherwise it must lead to large sheets of metal or a pile of coke buried deep enough to be always damp.* If the rod goes near any pipes or other masses of metal, they should be connected to it. Also any such masses of metal should be connected together wherever they approach each other.

Heavy galvanized iron telegraph-wire (No. 6 or 8) makes an excellent lightning-rod, while along the ridge-pole and around chimney-tops barbed fencing-wire may be used. All joints must be thoroughly made and then thoroughly soldered.

Perfect protection can only be obtained by enclosing the building in a complete metallic cage, covering the bottom as well as the top and sides of the building. The perfect protection of oil-tanks has not yet been accomplished.

372. Lightning-arresters. — Lightning-arresters are essential wherever telegraph, telephone, or electric-light wires enter a building. They ordinarily consist of a piece of metal connected with a good ground and brought near to the wire, so that the discharge will jump across the space rather than pass through the instruments. For high-pressure dynamo circuits a serious trouble is that the spark thus produced by the lightning is a good conductor, and the dynamo current follows the same path, forming an arc and quickly burning up everything in the neighborhood. Many ingenious devices for blowing out or destroying the arc have been found which effectively accomplish the result.

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* The ordinary practice of making a hole in the ground with a crowbar and sticking the end of the rod into it, makes a lightning-rod a source of danger rather than a protection.

CHAPTER XXVII.

SOME APPLICATIONS OF INDUCED CURRENTS.

373. The Telephone.—None of the applications of induced currents is more remarkable or more interesting than the telephone.

In its original form as devised by Bell it consists of a steel bar magnet with a coil of fine wire about one end, and a thin iron diaphragm placed as near as possible to the pole, but not touching it (Fig. 160). The whole is enclosed in a hard-rubber case which supports the diaphragm at a proper distance from the pole and serves as a handle.

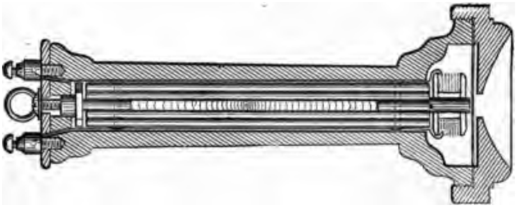

FIG. 160.—BELL TELEPHONE.

Whenever the iron diaphragm is near the magnet, it acts as a conductor for the lines of magnetic force, which go directly across from the pole to the diaphragm, off the edge of the latter, and thence to the more distant pole of the magnet (see Fig. 110, *C*). If the draphragm is more distant from the magnet, its influence is less marked, and the lines of force more nearly follow their ordinary direction (Fig. 110, *B*). Now if the diaphragm is moved from one position to another, the lines of force move at the same time, and in so doing many of them cut through the wires of the coil wound about the pole of the magnet.

374. The Sound Produces Electrical Vibrations.—Hence if one holds the telephone near his mouth and talks toward the diaphragm, the vibrations of the air set it into vibration, the lines of force swing back and forth, and a series of electric currents is induced in the coil which are *fac similes* of the sound vibrations. The coil in this telephone is connected to line wires, and at the farther end of these is another exactly similar instrument. The current set up in the coil of the first instrument is conducted through that of the second. Going around this coil in one direction it strengthens the pole about which it is wound, while in the opposite direction it weakens it, and thus the diaphragm will be attracted more or less strongly by the magnet. The vibratory current therefore sets the diaphragm of the second instrument into a series of vibrations exactly corresponding to those of the first telephone, and the voice of the original speaker is exactly reproduced.

375. The Carbon Transmitter.—In the instrument just described the receiver and the transmitter are identical. As the currents are produced by the vibrations of a diaphragm, they are very feeble and not suited for effective transmission over long lines. In modern practice a carbon telephone is used as transmitter. This depends for its action on the principle that the electrical resistance of carbon depends very much on the pressure to which it is subjected. An iron diaphragm has at its centre a stud of platinum and resting against this a hard button of carbon. As the speaker's voice sets the diaphragm into vibration there are corresponding variations in the pressure, and in the resistance, of the carbon. The platinum stud and carbon button are connected to the poles of a voltaic cell so that the current passes from one to the other. When, therefore, the resistance is decreased, a stronger current flows, and *vice versa.* Thus by the variations in pressure a varying electric current is maintained; and this current may be carried over the line to the distant telephone where by passing through the coil of the telephone, Fig. 160, it will reproduce its vibrations in the diaphragm of that instrument (now called the receiver); or, as is more frequently the case, the current is caused to pass through the primary coil of a small transformer whose secondary is connected with the main line.

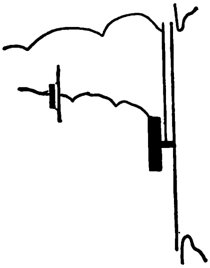

FIG. 161.—CARBON TRANSMITTER.

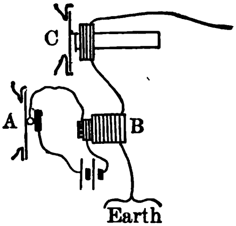

FIG. 162.—TELEPHONE AND CONNECTIONS.

376. No Sound Travels over a Telephone Line.—In all these cases it is to be noticed that no sound travels over the wire—simply a varying or alternating current, whose undulations, caused by the voice of the speaker, are reproduced in the motions of the receiving instrument.

377. Accessory Apparatus.—The voltaic cell used for telephone work is some form of the Laclanch ; this would polarize if left on a closed circuit; therefore when the instrument is not in use the circuit is broken by a switch which usually operates by hanging up the receiver. A calling apparatus is also connected with the line while the transmitter hangs up, which is really an alternator with permanent magnets. The alternating current passes around the electromagnet of a call-bell, whose armature is a permanent magnet which is alternately attracted and repelled. A ball on the end of the armature therefore vibrates back and forth between two bells which it strikes at each vibration.

The little transformer or induction-coil is wound with more turns of wire in the secondary than in the primary, and the electromotive force of the induced current is therefore higher than that of the primary. It is therefore better adapted for transmission over a line of considerable resistance. On the other hand, since the primary circuit has but small resistance, the variations in the resistance in the carbon button produce much greater variations in the current than if a high resistance were in the same circuit.

378. Induction-coils.—This principle of producing currents of high electromotive force from battery currents by means of a transformer is of considerable use in the laboratory. The apparatus employed for the purpose is called an induction-coil, and consists (Figs. 163 and 164) of a bundle of iron wires *a*, a coil of heavy wire *b* wound about the iron core, and a much larger coil of fine wire *c* wound out-

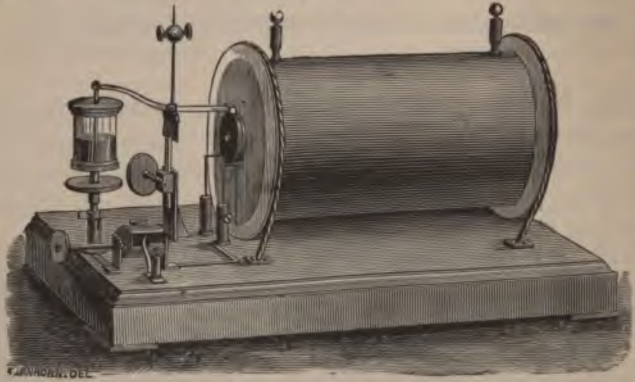

Fig. 163.

side the coarse coil and carefully insulated from it. The ends of the fine coil go to binding-posts on top of the coil *dd*, to which wires may be attached for carrying off the induced current. One end of the coarse-wire coil is attached to the post *e*, carrying a mercury cup; the other end goes to a spring *g*, then through a platinum-tipped wire to the mercury cup connected to *e*.

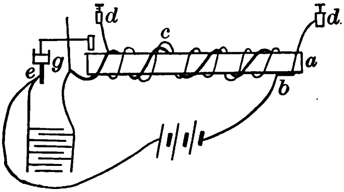

FIG. 164.

379. Use of the Coil.—Suppose the coil is to be used to send a high-pressure current through a Geissler tube. The tube is connected with the binding posts on top of the coil. To the coarse-wire coil are connected the poles of a battery of a few cells. A current flows through the thick-wire coil and magnetizes the iron core. An iron button on the spring *g* is attracted by the core and drawn downward, lifting the wire out of the mercury, and thus the circuit is broken; the current ceases, causing the lines of force to collapse, the spring flying back closes the circuit, and the operation is again repeated. Each time the iron is magnetized or demagnetized its lines of force cut through the wires of the fine coil, and there is an electromotive force of induction set up. This electromotive force is equal to the number of lines of force cut per second, and therefore depends upon three things: First, upon the whole number of lines of force. Hence a soft-iron core in which they may be easily set up, and a coarse-wire coil of little resistance, that the current in it may be strong. Second, upon the number of wires cut by the lines. Hence a secondary coil consisting of many turns of wire. The wire varies from a few hundred feet to several miles in length. Third, upon the rapidity with which the lines of force move. When the circuit is closed, the current increases somewhat slowly, and the electromotive force produced is relatively small. When it is broken, the current would stop instantly were it not for the self-induction of the primary coil, which resists such stopping. A bright spark is produced at the break, and the spark being a fairly good conductor allows the current to continue for a short time.

380. The Condenser.—To check this as rapidly as possible a condenser is added, as shown in the diagram. This consists of many sheets of tin-foil separated by paper. Each alternate sheet is connected in one set, the other sheets being in another set. One set is connected with the spring *g*, the other set with the post *e*, so that the "extra current" due to self-induction flows into the condenser instead of jumping across the gap. This of itself brings the current quickly to rest, but the charge in the condenser then flows back through the coil, reversing its magnetism and producing lines of force whose inductive effect increases the electromotive force of the secondary. The electromotive force on breaking the circuit is therefore very much greater than that on closing the circuit, and is the one which sends a current through the Geissler tube.

With an induction-coil a few cells of battery will keep up a torrent of sparks of a length varying from $\frac{1}{4}$ inch to one or two feet in length, according to the size of the coil.

381. Measurement of Electrical Resistance in Absolute C. G. S. Units.—There is one very important application of induced currents to be mentioned; namely, their use in measuring electrical resistance in absolute units. Electric currents are measured in absolute units by their effect in producing a magnetic field, as described on p. 134. The comparison of resistances has been described also, but for their absolute measurement the properties of induction are commonly employed. The resistance of a wire is defined to be the ratio of any electromotive force acting in the wire to the current which it produces; and to determine the resistance we require to know the electromotive force and the current. The first determination of this quantity was made in 1849 by Kirchoff.* Rowland's modification † of Kirchoff's method is as follows:

382. Rowland's Method.—A current from a battery B, Fig. 165, passes through a commutator K, an absolute tangent galvanometer G, and a carefully wound and measured coil of wire C_1. Near the coil C_1, and parallel with it, is a similar coil, C_2. From the measurements of the dimensions and distances of the coils it is possible to calculate how many lines of force are caused to pass through C_2 by any current in C_1. If this number is N for the current actually used, then when the current is reversed by the key K, N lines will be withdrawn from the coil C_2 and N others will be set up in the opposite direction. The whole change in the lines embraced by C_2 is therefore $2N$, and the whole flow of electricity produced in the secondary circuit is $\frac{2N}{R}$, if R is the resistance of that circuit. A ballistic galvanometer G_2 is

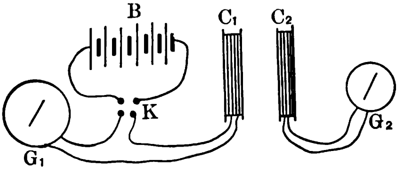

FIG. 165.

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* Pogg. Ann., vol. LXXVI. See Maxwell's Elec. and Mag., vol. II. p. 368.

† Amer. Jour. of Science, vol. XV., 1878.

placed in this circuit and measures the whole flow of electricity, and the resistance in absolute measure is found from the equation

$$q = \frac{2N}{R} \quad \text{or} \quad R = \frac{2N}{q}.$$

383. Lorenz's Method.—In the method employed by Lorenz * a brass disk is rotated in a magnetic field of known strength. A brush rests on the outer edge of the disk and another on the axle. As the disk rotates it cuts the lines of force which are perpendicular to it and produces a definite electromotive force, which can be calculated from the strength of the field and the speed of the disk. If this electromotive force is made to produce a current in a wire, the resistance of the wire may be determined as in the preceding case.

384. Joule's Method.—By measuring the heat evolved when a current passes through a wire † it is possible to determine the resistance of this wire from Joule's law that the heat per second is Ri^2. This method does not require the use of induced currents, but demands a knowledge of the number of mechanical units corresponding to one heat unit.

By these and other methods it has been found that a thread of mercury of one square millimeter cross-section and 106.3 centimeters long (see p. 166) has a resistance of very nearly 1 000 000 000 C. G. S. units.

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* Pogg. Ann., vol. 149, p. 251; 1873.

† See p. 172, and Joule's Collected Papers, vol. I. p. 572.

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